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SSD-TDR-64-209-SUPPLEMENT

BIOMEDICAL POTENTIAL OF A CENTRIFUGE IN AN ORBITING LABORATORY

TECHNICAL DOCUMENTARY REPORT No. SSD-TDR-64-209-SUPPLEMENT

JULY 1965

ASSISTANT FOR BIOASTRONAUTICS AND AEROSPACE MEDICINE
SPACE SYSTEM DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION, CALIFORNIA

Prepared under Contract No. AF04(695)-679 by
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Missile and Space Systems Division
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FOREWORD

This research program was conducted by the Missile and Space Systems Division (MSSD) of Douglas Aircraft Company, Inc., under the sponsorship of the Assistant for Bioastronautics and Aerospace Medicine, Space Systems Division, Air Force Systems Command, United States Air Force, Contract No. AF04 (695)-679 and supplemental agreement thereto. The report is augmented by directly related research data contributed by the Douglas Aircraft Company resulting from Independent Research and Development Program, Account No. 80241-001. Dr. W. J. White was the principal investigator for the Douglas Aircraft Company. The research sponsored by this contract was started in September 1964 and completed in February 1965.

This report is catalogued by MSSD as Santa Monica Report No. SM-48502. A previous report, entitled "Physiological Considerations Pertaining to Prolonged Weightlessness," was published in December 1964 as SSD-TDR-64-209 and as MSSD Santa Monica Report No. SM-47792. Some data presented in the earlier report are summarized here.

ABSTRACT

The results of several studies pertaining to manned orbital laboratories are reported.

The first of these studies concerns the consequence of heart-to-foot acceleration gradients for the measurement of tolerance to positive acceleration. A major finding of this study is that two modifications to the standard bioassay method -- a low-intensity central light and one gradual onset of acceleration to blackout -- make it possible to measure tolerance in the presence of a 219% heart-to-foot gradient with minimal cardiovascular stress.

The second was a parametric study of the power requirements of a short radius centrifuge. The findings here were (1) empty weight of the centrifuge is 155 lb, (2) peak power consumption is 436 watts, (3) energy consumption during a 7.5-min run at 4g is 5.85 Whr.

The third study is an analysis of the errors resulting from use of the centrifuge to determine body mass. The results of an error reduction study and the experimental apparatus for verifying the two-radius method are presented.

The salient generalizations derived from a series of studies in which bed rest was used as the analog of null gravity are presented.

The results of a pilot study to determine the influence of periodic centrifugation on the physiological disturbances associated with 41 days of bed rest are reported in the fourth study. The investigation was carried out during 20 days of bed rest, and 16 days of bed rest with periodic rides on the centrifuge, followed by 5 days of bed rest, centrifugation, and physical exercise. Major findings of this study were (1) motion sickness is not a problem for the well-trained individual when exposed to high angular rates of rotation and modest head or limb movements, (2) deterioration produced by recumbency in the ability to tolerate 90° head-up tilt for 20 min was largely alleviated by periodic centrifugation as judged by syncopal episodes, (3) the three subjects receiving +4 g_z four times each day showed less lability in blood pressure and heart rate during the tilt-table tests than did the two subjects exposed to +1 g_z.

The fifth study extended the results of the fourth study by increasing the integrated g-time from 0.5 and 2 g-hour to 3 g-hour, added approximately 700 kcal of exercise, and distributed the rides over a 24-hour period as contrasted with the 8-hour schedule of the fourth study. A maintenance group of three subjects began riding the centrifuge on the first day of bed rest and rode every day for 13 days. A therapy group of three subjects started riding the centrifuge after 17 days of bed rest and rode periodically for 6 days. A control

group of four subjects was transported to and from the centrifuge, but was not rotated. The major finding of this study was that the use of periodic centrifugation and exercise during bed rest tended to prevent deterioration, in the maintenance group, of the mechanisms essential for circulatory control on the tilt table. The effects of centrifugation were indicated by lack of syncope in the maintenance group as compared with three cases of syncope in the noncentrifuged group. The effects of exercise were indicated by heart rate responses during tilt.

As a result of these studies, the potential of the short-radius centifuge is presented, recommendations for future research are made; and the impact on future missions is examined.

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Section 1
INTRODUCTION

Orbital experiences and postflight medical examinations of American and Soviet astronauts have demonstrated cardiovascular deconditioning as a result of space flight, and have suggested that on prolonged flights the extent of such deconditioning may interfere with the astronaut's performance during re-entry and with his subsequent performance on Earth. This partial confirmation of earlier predictions strongly indicates a need for in-flight methods of alleviating these adverse effects.

Various methods of providing cardiovascular conditioning stimuli during orbital flights are shown in Figure 1-1. They range from the generation of a valid physiological acceleration through rotation, to the simulation of hydrostatic pressure effects with inflatable cuffs. Of the various rotational systems, the centrifuge is especially desirable from an engineering point of view in that it eliminates the extremely complex problems of designing and operating a rotating space station.* From a physiological point of view, the centrifuge has a demonstrated capability for generating a valid physiological stress. In addition, it is recognized as a tool for physiological investigation and as a training device because it simulates the accelerations encountered in aerospace operations. Before the centrifuge can be considered for inclusion in a manned orbital laboratory, certain engineering and physiological problems must be solved.

Little is known about either the beneficial or the deleterious effects on man of periodic exposure to acceleration on a short-radius centrifuge. Rate of onset, magnitude of acceleration, and time of exposure are important to the engineer designing an on-board centrifuge; and there is little information as to what these parameters should be. As a result, the designer lacks much

*Douglas Aircraft Co., Inc., Report on a System Comparison and Selection Comparison and Selection Study of a Manned Orbital Research Laboratory, Vol. I, Technical Summary, Appendix 2, Experimental Program, Final Report NAS 1-2974, Santa Monica Report No. SM-44598, September 1963.

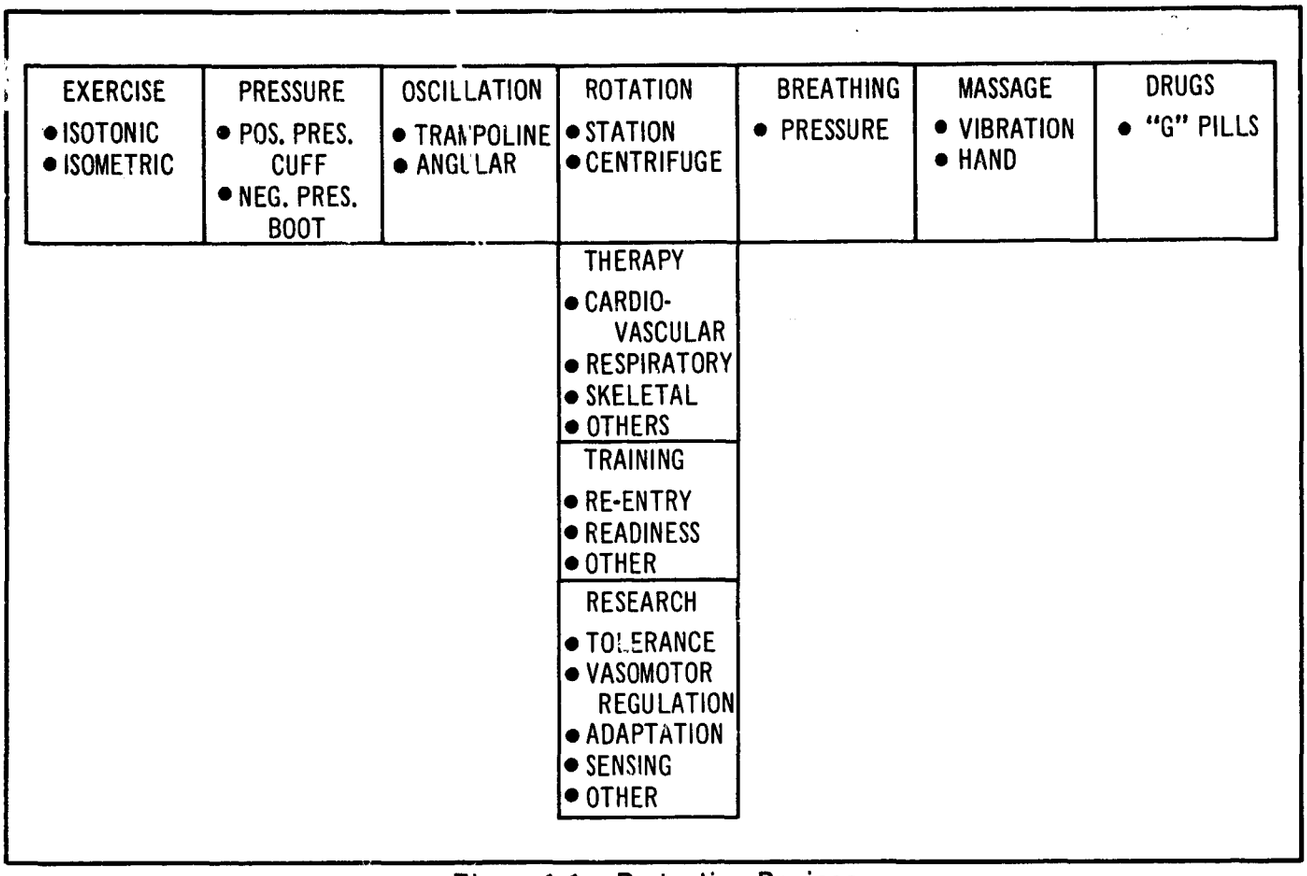

Figure 1-1. Protective Devices

of the information necessary for preliminary vehicle sizing studies, and, similarly, the physician responsible for the welfare of the space crewmen cannot verify the physiological efficacy of periodic centrifugation.

Clearly, studies are needed to determine the following:

1. The effectiveness of a short-radius (4.5 ft) centrifuge in counteracting the physiological effects of null gravity.
2. The deleterious effects, if any, on man resulting from exposure to acceleration on the short-radius centrifuge.
3. The best combination of frequency, duration, and magnitude for optimum beneficial effects and minimum deleterious effects.
4. The tolerance to $+g_z$ acceleration on the short-radius centrifuge.
5. Precision of short-radius centrifuge in determining body mass.
6. The design variables associated with the use of the short-radius centrifuge in an orbital laboratory.

The present studies have been concerned primarily with a quantitative demonstration of the feasibility and general effectiveness of a short-radius centrifuge under the following conditions:

1. As a test device for measuring acceleration tolerance before, during, and after a period of recumbency.
2. As a means of measuring body mass in orbit.
3. As a means of alleviating or preventing adaptation of the cardiovascular system to horizontal positioning as the result of bed rest.

The present studies are exploratory. Although it is clear that they are not likely to specify optimum conditions for the use of the centrifuge in orbit, they do represent a pioneering step in the direction of defining biomedical potential of an on-board centrifuge, and in arriving at a measure of relative effectiveness of protective devices.

Section II

CONSEQUENCE OF HEART-TO-FOOT GRADIENT FOR THE MEASUREMENT OF TOLERANCE TO POSITIVE ACCELERATION

In addition to its potential as a deconditioning countermeasure, the short-radius centrifuge shows promise as a tool for studying gravity-influenced physiological systems in space. Its use in an orbital research laboratory may make possible the study of cardiovascular mechanisms that would be difficult, if not impossible, to study by any other means. Clearly, studies are needed to determine the effectiveness of the short-radius centrifuge as a research device and the deleterious effects, if any, on man of exposures to large heart-to-foot acceleration gradients.

Although considerable research has been conducted on the effects of distributed accelerative forces on man (References 2-1, 2-2, 2-3), little research has been done on the effects of steep acceleration gradients inherent in the use of a short-radius centrifuge. As a first step in the evaluation of the potential of an on-board centrifuge system, Piemme, Hyde, McCally and Potor (Reference 2-4) measured the duration of human tolerance to positive acceleration at a 256% heart-to-foot acceleration gradient (the subjects were in a seated body position).* They found that acceleration levels of 1, 2, and +3 g_z (referenced to the feet) were tolerated by all subjects for 2 hours, except for one subject who became nauseated following head movements after 28 min at +3 g_z. Above these levels, mean tolerance times were +4 g_z for 108 min 25 sec, +5 g_z for 26 min 40 sec, +6 g_z for 8 min 8 sec, and +7 g_z for 2 min 41 sec. Comparison of the Piemme, et al., stress-duration curve with that of Miller, Riley, Bondurant, and Hiatt (Reference 2-5), at comparable levels of acceleration, shows that subjects

*Acceleration gradient is equal to the acceleration at the feet (g) minus the acceleration at the heart (g) divided by the acceleration at the heart. Multiplication by 100 converts this expression to percentage and represents the physical gradient applied to the subject.

can ride the short-radius (4.75 ft) centrifuge for a longer time than subjects could ride a long-radius (23 ft) centrifuge.

A second step in evaluating the potential of the on-board centrifuge is the discovery of the significance of the acceleration gradient in the measurement of acceleration tolerance. The consequence of heart-to-foot acceleration gradients for tolerance to positive acceleration ($+g_z$) was studied on a variable radius centrifuge. Gradients ranging from 20 to 219% were examined in three studies. The effects of rates of onset of acceleration on tolerance were studied at radii of 16 and 156 in. (referenced from center of rotation to heart level).

2.1 METHODS

Six healthy, male subjects participated in the first study. Their ages ranged from 21 to 28 years. All were experienced in riding the centrifuge. The radii used in this study (referenced from the center of rotation to the third intercostal space) were 172, 112, 58, and 30 in. The heart-to-foot acceleration gradients at these radii were 20, 31, 60, and 116%, respectively. Acceleration tolerance was measured, based upon the standard bioassay technique. Blackout is defined when the subject fails to respond to the illuminated central light by operating a switch to turn off the light. Standard intensity bioassay lights were used, that is, 30 ft-L. The runs began at +3 g_z and subsequent runs were made at 0.2 g increments until blackout was reached. Time at peak acceleration was 15 sec. The rate of onset of acceleration was 0.2 g/sec.

In the second study, a modification of the conventional bioassay method was used. It has been shown in previous studies (Reference 2-6) that a reduction in the intensity of the bioassay lights results in a blackout at lower levels of acceleration and implies that the visual changes that precede blackout can be used as an index for the determination of physiological stress. On the basis of this approach, the central bioassay light was fitted with a red filter and the light intensity was adjusted to 0.2 logarithmic units above foveal threshold. The subject responded to this light in the conventional

manner by turning it off when it appeared. Failure to cancel the central light was taken as blackout and the acceleration at that point was taken as tolerance. At this point, a second but brighter peripheral light was turned on. When the second light was cancelled, the subject signalled, in effect, that the predicted visual changes had taken place and the run was terminated. For reasons of safety and convenience, it was desirable that the subjects should not ride the centrifuge in complete darkness. For these reasons, the subjects wore light-tight goggles fitted with red lenses of suitable density. As a result, television monitoring of the subject was possible during centrifugation.

Tolerance was measured at two radii and two rates of onset. Different rates of onset were used to determine their effects on the level of blackout. The first series of runs was made at a 156-in. radius and a 22% gradient to establish the validity of the modified bioassay technique. Following this series, the radius was decreased to 16 in., resulting in a 219% gradient. Rates of onset were 0.2 g/sec and 3.0 g/sec at the long radius and 3.0 g/sec at the short radius. A total of 10 healthy, male subjects participated in this second study. Each subject received three bioassay runs at the 156-in. radius at both fast and slow rates of onset, and one to three runs at the short radius. In the conventional bioassay method used in this study, the magnitude of peak acceleration is increased by 0.2 g in successive runs until blackout is reached. Peak g is maintained for 15 sec when standard lights are used, and for 30 sec when the low-intensity central light is used. This technique requires a number of runs before acceleration tolerance is reached. Because repeated stress of the cardiovascular system is undesirable, the use of a less stressful approach is indicated.

In the third study, the number of runs required for determining blackout was reduced to one. A gradual onset of acceleration (0.2 g/sec) to blackout was used. The acceleration at which the subject failed to respond to the low-intensity central light was taken as tolerance threshold. Failure to respond to the light and the auditory signal (buzzer) was categorized as a loss of consciousness. Gradual deceleration was begun as soon as the central light was lost. Because of the large gradient, +4 g_z at the heart

was set as an arbitrary upper limit. The radius from the center of rotation to heart level was 16 in., which resulted in a gradient of 219% from the heart to the feet. To preclude discomfort in the lower extremities, the subjects' calves and feet were lightly wrapped with ace bandages. A previous study (Reference 2-7) has shown that ace bandages applied in this manner have little or no effect upon acceleration tolerance.

2.2 RESULTS

The results of the first study are shown in Table 2-I and Figure 2-1. In Table 2-I, the acceleration levels at which blackout occurred for the six subjects are shown for each radius. The table also shows the number of runs made by each subject in calculating his mean tolerance threshold. Mean tolerance was +3.9 g_z at the 172-in. radius, +4.4 g_z at the 112-in. radius, and +4.6 g_z at the 58-in. radius. These data reveal an increase in acceleration tolerance with decreasing radius. This relationship probably

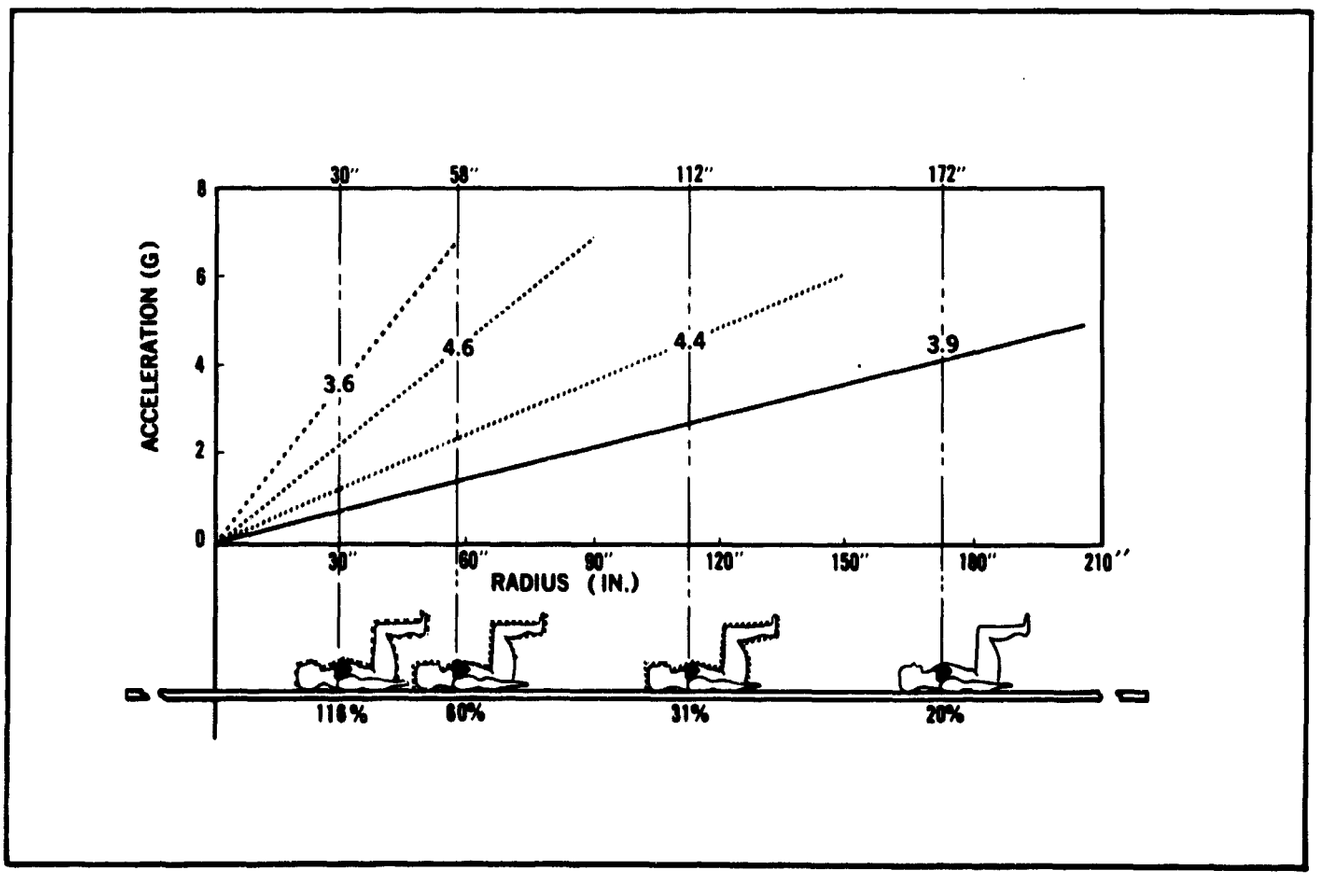

Figure 2-1. Force Environment at Different Radii

Table 2-I

ACCELERATION TOLERANCE AT DIFFERENT RADII

SUBJECT	RADIUS - CENTER OF ROTATION TO HEART							
	30 In. *		58 In.		112 In.		172 In.	
	$+G_z$	N	$+G_z$	N	$+G_z$	N	$+G_z$	N
K B	3.6	2	-	-	4.5	1	4.0	8
B B	3.6	2	4.8	1	4.6	1	4.0	7
R E	3.6	3	5.0	2	4.6	1	4.2	6
R H	3.6	1	-	-	5.0	1	4.5	5
N K	3.6	2	4.4	3	4.3	2	3.5	8
B S	3.6	1	4.0	1	3.6	3	3.4	7
MEAN	3.6	-	4.6		4.4		3.9	

Entries are in $+g_z$ units at heart level.

* All runs at this radius were terminated at +3.6 g_z (at the heart) because of discomfort or pain in the calf, ankle, or foot.

reflects a tendency of the subjects to tense their leg muscles to relieve fullness or discomfort produced by the acceleration gradient. Also, it is to be noted that the number of repeat runs was small at the 58- and 112-in. radii. At a radius of 30 in., blackout was not obtained; discomfort or pain occurring in the unprotected calves and feet precluded attainment of the visual symptoms of acceleration (cf., the second and third studies). The highest tolerable acceleration at the 30-in. radius was +3.6 g_z at the heart. At this level, the acceleration at the feet was +7.8 g_z. Scattered petechial hemorrhages were observed on the feet and ankles of the subjects after runs at the 30-in. radius; these cleared in 2 to 3 days. No edema or muscular abnormalities were noted. No unusual discomfort was reported by the subjects at other radii. Although symptoms of vestibular stimulation such as nausea were not noted by the subjects, they did report some transient "dizziness" when rotating their heads forward. These symptoms lasted only momentarily with no noticeable effects after centrifugation.

Figure 2-1 depicts the force environment at different centrifuge radii. The angular velocities from the longest to the shortest radii at mean tolerance levels were 28, 37, 53, and 65 rpm. Tolerance runs were made with the subjects in the seated position.

The results of the second study are shown in Table 2-II. The average acceleration required to produce blackout at the 156-in. radius and 0.2 g/sec onset rate was +3.9 g_z, and +3.8 g_z at the 3.0 g/sec onset rate. The subjects reported no unusual discomfort in their lower extremities at this radius. Average acceleration tolerance at the 16-in. radius was +3.0 g_z. All subjects noted discomfort in their lower extremities but all except two were able to complete their runs. These two subjects developed intense discomfort in their legs prior to blackout and their runs were terminated. Physical examination of the subjects after bioassay runs at the long radius revealed only scattered petechial hemorrhages on the feet and ankles of several subjects; these cleared in 2 to 3 days. After bioassay runs at the short radius, petechiae were observed on the feet and ankles of most subjects. Several had minimal edema of the same areas; this condition disappeared within 1 to 2 hours. Transient fullness and mild tenderness

Table 2-II

ACCELERATION TOLERANCE - MODIFIED BIOASSAY METHOD

(LOW-INTENSITY CENTRAL LIGHT)

SUBJECT	RADIUS - CENTER OF ROTATION TO HEART		
	156 In.		16 In.
	0.2 G/Sec	3.0 G/Sec	3.0 G/Sec
KB	3.9	3.9	3.9
LB	4.2	4.3	(3.7)*
LH	3.0	3.2	2.6
RH	4.0	3.8	(3.1)*
GK	4.5	3.9	2.9
NK	3.9	3.5	3.2
GL	3.6	3.7	2.8
GM	3.6	3.7	2.8
BS	3.8	3.7	3.4
BW	4.2	3.9	3.2
MEAN	3.9	3.8	3.0

Entries are in $+g_z$ units at heart level.

*Terminated because of pain in legs; not included in the mean.

to palpation of the calf muscles were noted on several subjects. One subject reported mild generalized tenderness in his calf muscles, when walking, for a period of 24 hours after one run at the short radius. Symptoms related to vestibular stimulation were no different from those experienced during the first study. Limited head and limb movements were possible at both radii.

Bioassay determinations during the third study were made on three separate occasions. The results are shown in Table 2-III. At the time of the initial determinations, the subjects showed an average tolerance of +3.6 g_z. Two runs were terminated after reaching the preset maximum of +4 g_z without the subjects blacking out, and two runs were terminated because the subjects experienced intense discomfort in their legs. Determinations made during the latter two occasions revealed average tolerances of +3.3 g_z and +3.4 g_z. All subjects reached blackout except one whose run was terminated because of intense pain prior to blackout. Four subjects did not respond to the lights or buzzer for a few moments during the deceleration phase of their runs; therefore, by definition they were unconscious. After all runs in this third study, the subjects had engorged veins in their lower extremities which returned to normal within a few minutes. A few subjects developed minimal edema of their feet and mild tenderness of their calf muscles which cleared within a few hours. Most subjects developed petechial hemorrhages, ranging from a few to many, on their feet and ankles; this condition disappeared in 2 to 3 days.

2.3 CONCLUSIONS

The influence of acceleration gradients, ranging from 20 to 219%, on tolerance to positive acceleration (+g_z) has been investigated in three studies using a variable-radius centrifuge. Data from these studies show the following:

1. As the radius decreases and the gradient increases, there is a tendency for blackout tolerance to increase.
2. At steep gradients (for example, 116% and larger), discomfort and pain in the calves and feet precludes the use of the standard bioassay method for determining tolerance.

Table 2-III

ACCELERATION TOLERANCE - MODIFIED BIOASSAY METHOD

(LOW-INTENSITY CENTRAL LIGHT AND GRADUAL ONSET OF ACCELERATION TO BLACKOUT)

SUBJECT	DATE OF DETERMINATION		
	B-3	T-15, T-16	BR-2
JA	4.0*	3.2	3.5
CB	4.0	3.5	3.4
RE	4.0*	3.5	3.4†
HK	3.2	3.2†	3.1†
RM	(3.3)●	3.0	3.4
GM	3.5	3.2	3.5
LS	(3.5)●	2.4	(3.3)●
FS	3.8	4.0†	3.8
MEAN	3.6	3.3	3.4

Entries are in $+g_z$ units at heart level.

* Terminated at maximum g; not included in mean.

† Became unconscious during decay after central light loss.

● Terminated because of pain in legs; not included in mean.

3. Two modifications of the standard method -- a low-intensity central light and one bioassay run with gradual onset of acceleration -- make it possible to determine tolerance to acceleration in the presence of steep heart-to-foot gradients with minimal cardiovascular stress.

4. Low-intensity bioassay lights can be used either with rapid or slow onset of acceleration with comparable results.

5. Further refinements in bioassay techniques are needed to reduce the number of complaints of discomfort and pain in the calves and feet and also to reduce the number of runs during which subjects reach the maximum level of acceleration without attainment of blackout.

6. A steep heart-to-foot acceleration gradient is not accompanied by motion sickness in the experienced subject, and high angular velocities do not preclude limited head or limb movements.

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Section III
CENTRIFUGE DESIGN CONSIDERATIONS

In considering the use of a short-radius centrifuge in an orbital laboratory, attention must be given to power consumed by the drive system. Peak-power requirements are dependent upon the rate of onset of acceleration required to produce the desired physiological consequences. These tradeoffs are of paramount importance to design and system engineers.

The operational envelope available in a 10-ft nominal diameter space laboratory leaves little choice in the configuration of the centrifuge. Figure 3-1 shows the most likely configuration with a counterbalance of storable materials. The materials used in the counterbalance are those required during the final phases of orbital flight and entry.

3.1 POWER REQUIREMENTS

Power requirements are influenced greatly by onset rate. The following is a parametric study of the power requirements for a 52-in. radius centrifuge showing the influence of onset rate on power requirements.

The system under consideration is mounted on pivot bearings at the center of rotation. It operates in an enclosed volume which forces the enclosed air to rotate with the centrifuge. Power requirements are determined from the power required to accelerate to speed, power losses caused by aerodynamic drag, bearing friction, and drive-train losses. The calculations are based on the counterbalanced centrifuge and the following data:

Empty weight of system	155 lb
System mass moment of inertia (including 180-lb crewmen)	120 slug-ft^2
G-force at feet	+4 g_z
Radius at feet	52 in.
Rotational velocity	52 rpm

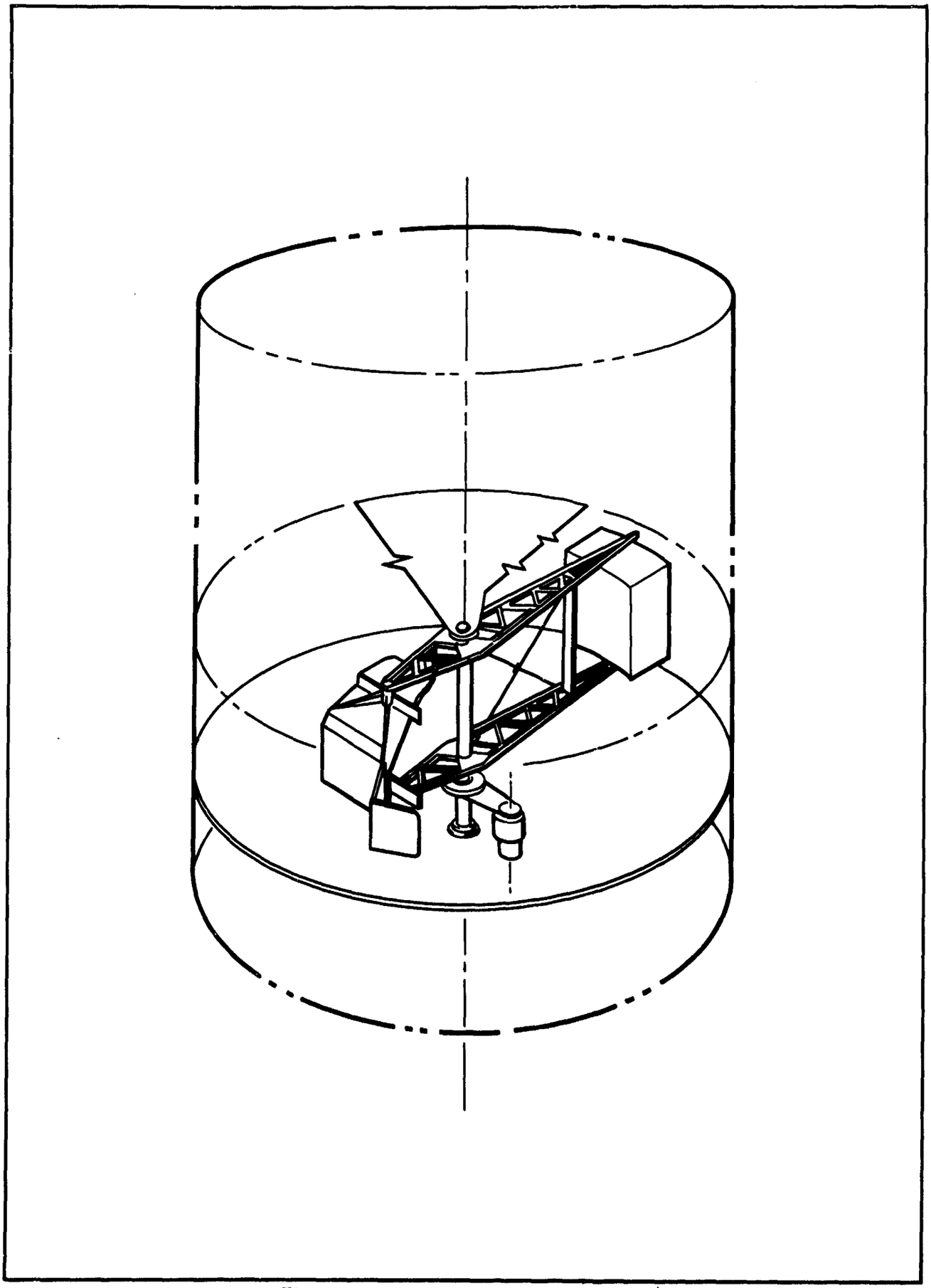


Figure 3-1. Space-Based Centrifuge Concept

Power drive-train efficiency	88%
Motor efficiency--steady state	65%
Motor efficiency--accelerating	55% average

Aerodynamic drag is estimated by assuming that the total mass of air in the volume swept by the centrifuge rotates at centrifuge speed and that the power loss is predominantly from viscous drag at the walls. This estimate is based on turbulent boundary-layer theory. At centrifuge rpm this loss amounts to 1.85 ft-lb of frictional torque, or a power loss of 13.7 watts. This power loss contrasts with the losses from a similar centrifuge rotating in an open room where the drag approaches flat-plate drag of the centrifuge elements, bringing about a power loss of approximately 93 watts.

Bearing friction is not expected to exceed 0.58 ft-lb. This value is a power loss of 4.3 watts at 52 rpm.

The total running friction losses amount to 2.43 ft-lb, which is equivalent to a full-speed power loss of 18.0 watts. Applying factors of 80% for drive-train efficiency and 65% for motor efficiency, the power input to the system to overcome friction losses amounts to 34.6 watts.

The purpose of the above loss determination is to establish first-order approximations, rather than to ascertain precise values. For rates of onset as low as 0.2 g/sec, at the subject's feet, the friction power loss is approximately one-tenth of the power required to accelerate the centrifuge, and is less significant at higher rates of onset. The steady-state power losses become significant for running times on the order of 7.5 min. During a 7.5-min run, a total of 4.32 Whr will be consumed by friction torque.

This discussion considers the power required to accelerate the centrifuge. The acceleration torque is reacted against the laboratory. During acceleration of the centrifuge, a laboratory with a rolling moment of inertia of 10^4 slug-ft^2 will accelerate, if uncorrected, to 0.655 rad/sec or 0.625 rpm. If the laboratory is restricted from rotation, 0.655 lb of reaction-control propellant will be required for each spin-up and spin-down, on the basis of an I_{SP} of 200 sec and reaction jets mounted on a 5-ft radius. If the

acceleration torque is reacted by an inertia wheel instead of the laboratory, the reaction-control fuel will be saved, but additional energy must be expended to accelerate the inertia wheel.

Because of the atmospheric contamination and brush-life problems in a reduced-pressure and oxygen-enriched atmosphere, the use of an induction or a synchronous ac motor with variable frequency speed control appears preferable to a direct-current motor. A representative speed-torque curve is shown in Figure 3-2, and is used to determine peak power as a function of rate of onset of acceleration at the subject's feet. Peak power, average power, and time to full speed are plotted as a function of average onset rate in Figures 3-3 and 3-4. Figure 3-4 is an amplification of Figure 3-3 in onset range from 0 to 1 g/sec. Peak rate of onset for this system is approximately twice the average rate of onset.

Based on this study, it seems unwise to use onset rates in excess of 0.2 g/sec at the feet unless there are therapeutic or test advantages to be gained. This rate of onset represents acceleration to full speed in 20 sec. At this rate of onset, peak-power consumption would be approximately 436 watts for the assumed motor characteristics, with an average power expenditure of 275 watts. At the above rates, during a 7.5-min full-speed run, the energy consumption would be 5.85 Whr. Approximately 1.53 Whr of the 5.85 is in the form of kinetic energy of rotation in the centrifuge and could be reclaimed with suitable power-conversion equipment.

3.2 SUMMARY

A parametric study to determine the power requirements of a short-radius, on-board centrifuge reveals the following:

1. An on-board centrifuge would have a total empty weight of approximately 155 lb.
2. Peak-power consumption at 0.2 g/sec rate of onset is approximately 436 watts.
3. Energy consumption during a full-speed run for 7.5 min is 5.85 Whr.
4. Onset rate should not exceed 0.2 g/sec at the feet unless justified by special requirements.

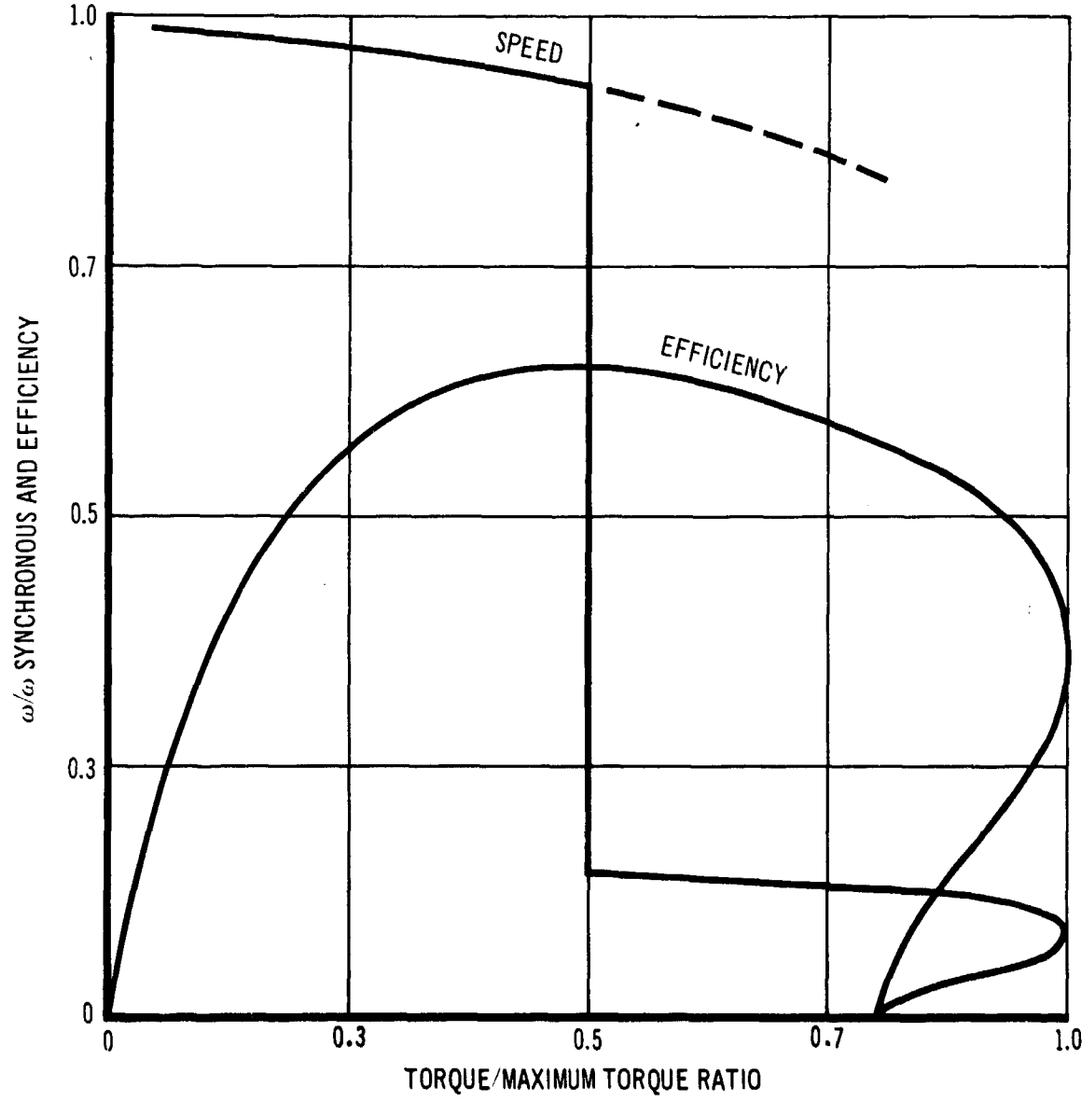
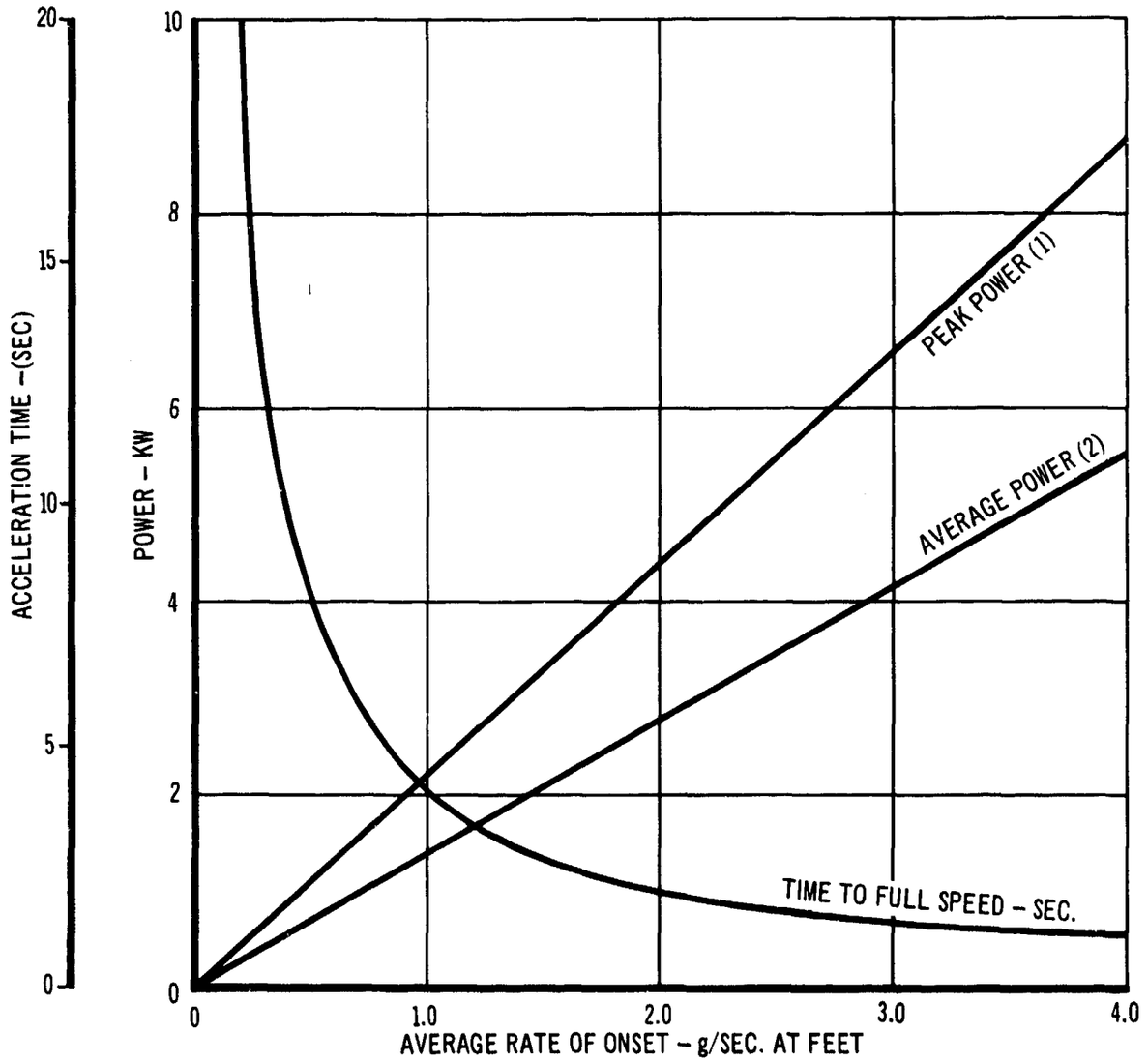


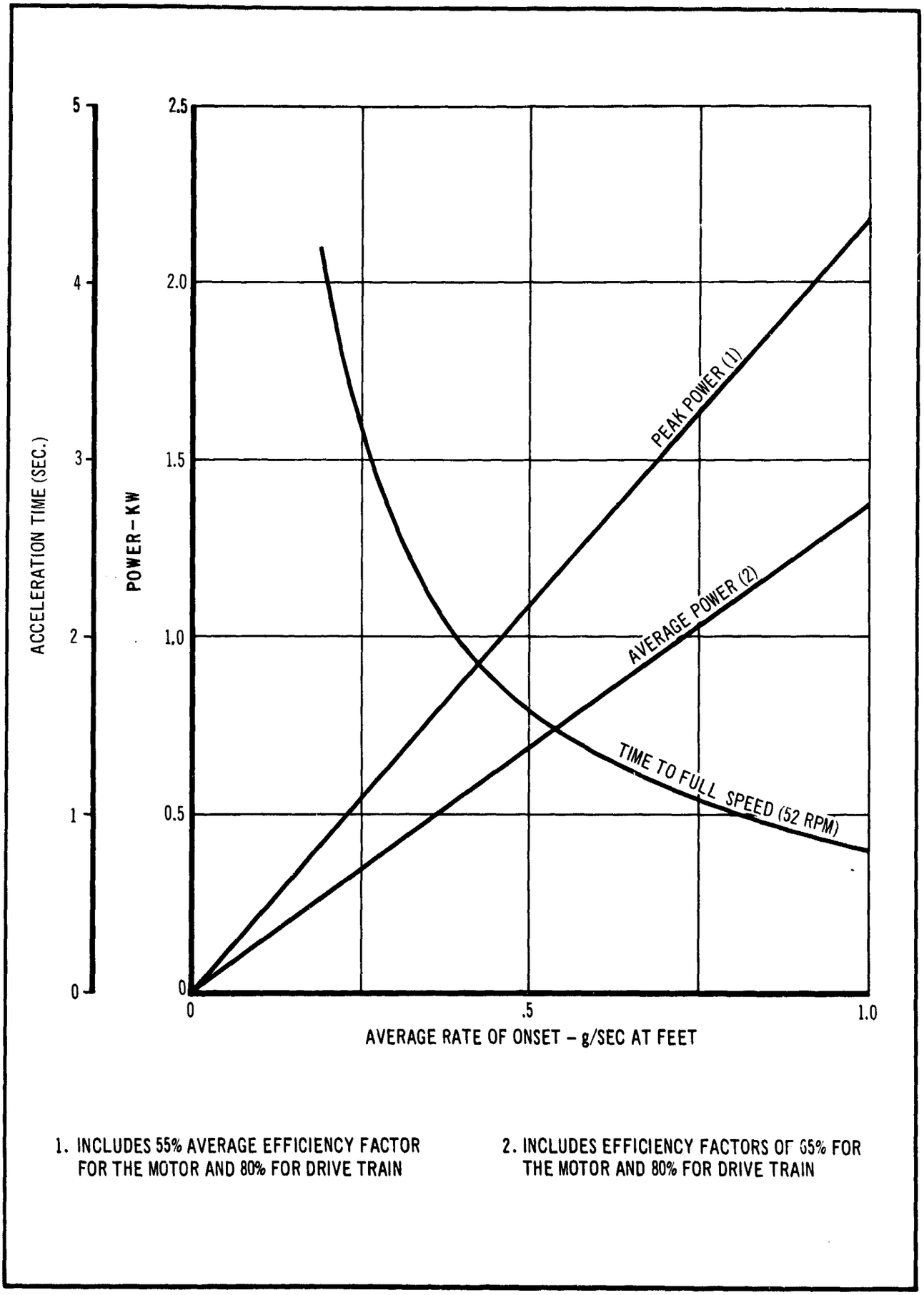
Figure 3-2. Speed and Efficiency as a Function of Torque for a Typical Motor



1. INCLUDES 55% AVERAGE EFFICIENCY FACTOR FOR THE MOTOR AND 80% FOR DRIVE TRAIN

2. INCLUDES EFFICIENCY FACTORS OF 65% FOR THE MOTOR AND 80% FOR DRIVE TRAIN

Figure 3-3. Centrifuge Power Required as a Function of Onset Rate



1. INCLUDES 55% AVERAGE EFFICIENCY FACTOR FOR THE MOTOR AND 80% FOR DRIVE TRAIN

2. INCLUDES EFFICIENCY FACTORS OF 65% FOR THE MOTOR AND 80% FOR DRIVE TRAIN

Figure 3-4. Centrifuge Power Required as a Function of Onset Rate (Amplified Scale)

Section IV

ANALYSIS OF THE CENTRIFUGE TO DETERMINE BODY MASS

Orbital determination of the mass or weight of a subject is desirable for biomedical monitoring. Various mass measuring methods are under consideration (Reference 4-1). They range from the most common means of weighing on the Earth--the spring scale and beam balance--to sophisticated methods such as measuring the body's opacity to X-rays. The more common methods are (1) energy-velocity, (2) vibrating spring and masses, (3) momentum, and (4) centrifuge.

The energy-velocity method uses a spring with a known amount of stored energy to impart a velocity to the mass to be measured and the space laboratory mass. The mass of the man and his carrier is determined from the principle of conservation of energy.

The vibrating-spring-and-masses method takes advantage of the natural frequency of vibration of two masses (the station mass and the mass to be measured) coupled together by a spring of known spring constant.

The momentum method uses a small mass of known or determinable velocity to collide with and stick to the carriage on which a man is mounted. The velocity after impact is measured over a finite distance, and the unknown mass is determined from the law of conservation of momentum.

If the centrifuge is required aboard a space laboratory for cardiovascular conditioning, mission-oriented research, or re-entry training, it is prudent to consider its utility in "weighing" space crews.

The basic parameter from which weight can be deduced is the centrifugal force. Centrifugal force is related to mass and thus weight by the familiar centrifugal force expression:

$$F_c = M\omega^2 r \tag{4-1}$$

F_c = Centrifugal force - lb

M = Mass of the object being rotated = $\frac{W}{g} = \frac{\text{Weight}}{\text{Acceleration of gravity at Earth's surface}}$

ω = Angular velocity - rad/sec

r = Radius from the center of rotation to the center of mass to be weighed

Equation (4-1) can be rearranged as follows:

$$M = \frac{W}{g} = \frac{F_c}{\omega^2 r} \tag{4-2}$$

$$W = \frac{F_c g}{\omega^2 r}$$

To appraise the relative accuracy of a method based on the subject parameters, it is well to determine how the indicated weight varies with the variation of the other parameters.

4.1 ERROR ANALYSIS

It can be said that

$$W = Kf(F_c, \omega, r)$$

where K is a constant of proportionality equal to 32.2 ft/sec^2.

Using the chain rule of partial differentiation

$$\Delta W = \frac{\partial W}{\partial F_c} \Delta F_c + \frac{\partial W}{\partial \omega} \Delta \omega + \frac{\partial W}{\partial r} \Delta r \tag{4-3}$$

From Equation 4-2

$$\frac{\partial W}{\partial F_c} = \frac{g}{\omega^2 r} = \frac{W}{F_c}$$

$$\frac{\partial W}{\partial r} = \frac{F_c g}{\omega^2 r^2} = -\frac{W}{r}$$

$$\frac{\partial W}{\partial \omega} = -\frac{2F_c g}{\omega^3 r} = -\frac{2W}{\omega}$$

Substituting into Equation 4-3

$$\Delta W = W\left(\frac{\Delta F_c}{F_c} - \frac{\Delta r}{r} - \frac{2\Delta\omega}{\omega}\right) \qquad (4\text{-}4)$$

$$\Delta W = (\pm e_{F_c} \pm e_r \pm 2\, e_\omega)$$

$$e_{F_c} = \frac{\Delta F_c}{F_c} = \text{the error in } F_c$$

$$e_r = \frac{\Delta r}{r} = \text{the error in } r$$

$$e_\omega = \frac{2\Delta\omega}{\omega} = \text{the error in } \omega$$

An examination of each of the errors in turn is in order.

4.1.1 The Error in Centrifugal Force Measurement - e_{F_c}

The maximum error in F_c, on the basis of Douglas experience which has called for great care in weighing Saturn vehicles, will not exceed 1/10% or 0.001.

4.1.2 The Error in the Radius to the Center of Mass - e_r

The center of mass of the human body is difficult to determine because the body is composed of a series of highly elastic masses coupled to each other by springs of varying constants. Changes in body fat can cause a variation of inches in the position of the center of mass while in the seated position. Varying angular velocities will cause the internal organs to shift position, resulting in a change in the mass center. It is doubtful if the location of the human mass center can be located within 2 in., especially over a long period of time when sizable changes in body fat could occur. Since the effect of error in radius is $\frac{\Delta r}{r}$, Figure 4-1 shows the percentage of error as a function of centrifuge radius from the center of rotation to the center of mass of the human subject. It can be seen from Figure 4-1 that an error of ±8.3% can be incurred because of the uncertainty in r.

4.1.3 The Error in Angular Velocity Measurement - e_ω

The Douglas centrifuge is equipped with a pulse generator that pulses 600 times/revolution. The pulses are counted and divided by a time scale in a digital counter. Revolutions/minute are read digitally to the nearest 0.01 rpm. This error of ±0.01 multiplied by $2\pi/60$ equals ±0.00104 rad/sec.

The likely operating range of the centrifuge is from 20 to 60 rpm, which is from 2.1 to 6.3 rad/sec. Figure 4-2 shows a plot of $\left(\frac{2\Delta\omega}{\omega}\right)$ as a function of rpm.

4.1.4 Boundary of Uncertainty Based on Use of a Short-Radius Centrifuge for Mass Determination

A sample problem can now be processed. Assume a 180-lb man being weighed on the centrifuge, at r = 24 in. and 52 rpm.

$$W = 180 \pm (\Delta W)\, e_r = 0.083$$

$$W = 180\,(1 \pm \Sigma_e)\, e_{F_c} = 0.001$$

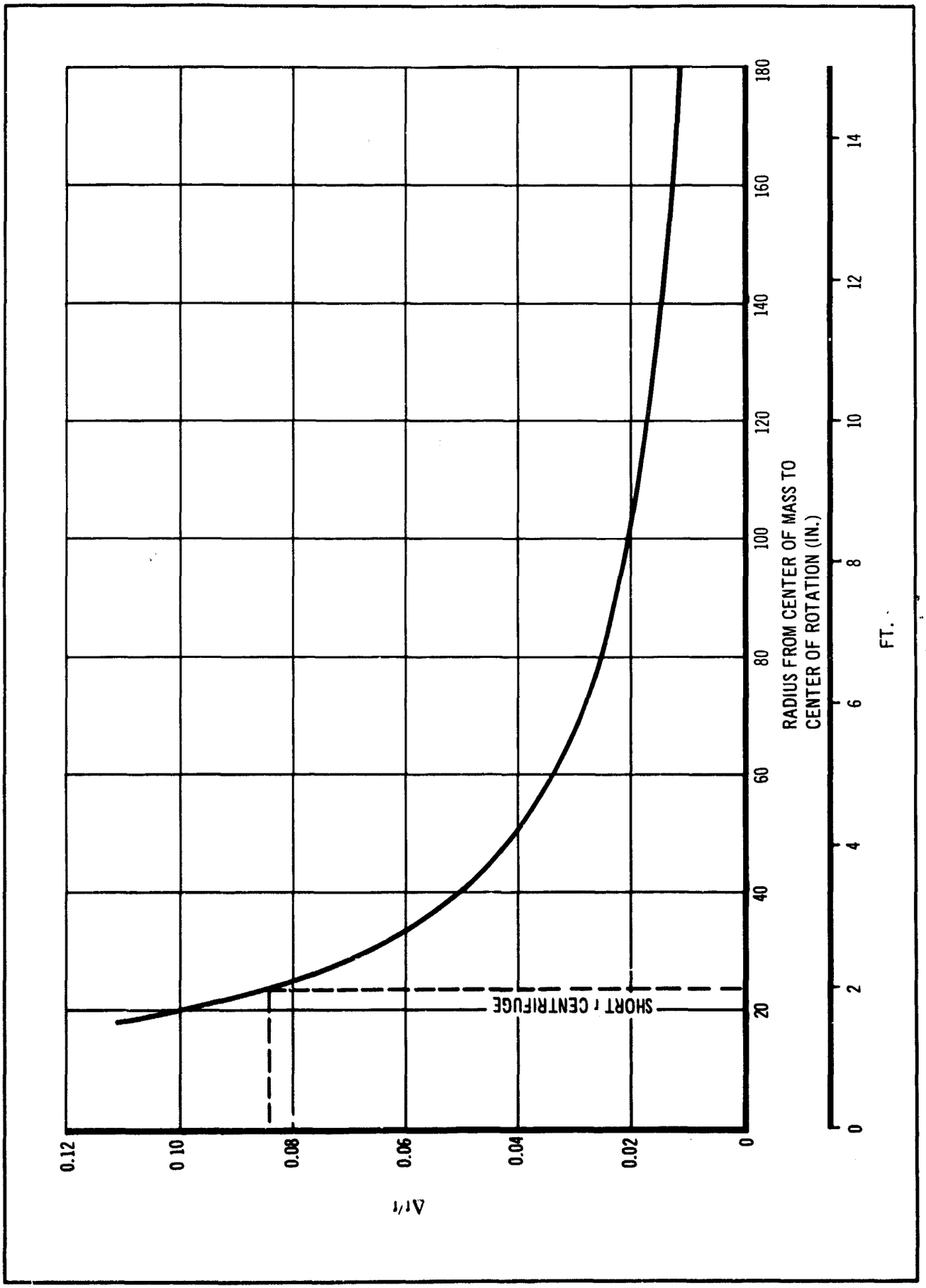


Figure 4-1. Effect of an Uncertainty of 2-In. on the Error in r as a Function of Centrifuge Arm Radius

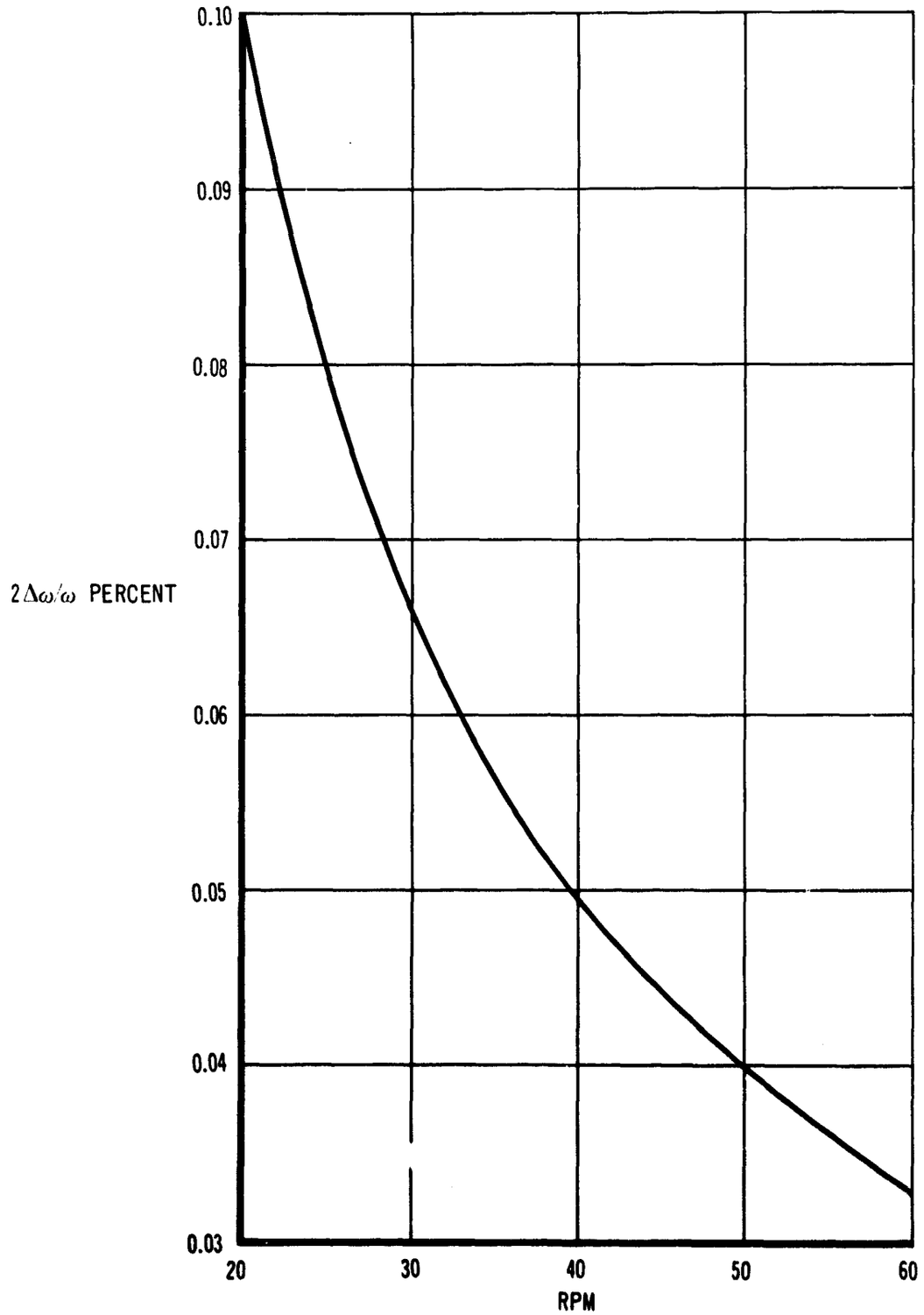


Figure 4-2. Error in ω as a Function of Centrifuge RPM

$$e_\omega = 0.000382$$

$$\Sigma_e = 0.084382$$

$$W_{max} = 180\ (1.084382) = 195.18876\ \text{lb}$$

$$W_{min} = 180\ (0.915618) = 164.81124\ \text{lb}$$

The bounds of uncertainty are ± 15.18876 lb in the weight of the 180-lb subject by straight configuration.

4.2 ERROR REDUCTION--TWO-RADIUS METHOD

The most important source of error in the calculation in Section 4.1.4 is the uncertainty in r, the radius from the center of rotation to the center of mass of the subject to be weighed. It would be most profitable to eliminate r as a variable from the weighing process.

This can be done by measuring the centrifugal forces with the subject mounted at two different distances from the center of rotation. First, a force F_1 is recorded at a radius r and at an angular velocity ω_1. The subject is then moved a fixed distance Δr along a ray line to a new radius $r + \Delta r$. A second centrifugal force F_2, preferably as close to F_1 as possible, is recorded at an angular velocity ω_2. These forces are expressed mathematically as follows:

$$F_1 = M\omega_1^2 r \qquad (4\text{-}5)$$

$$F_2 = M\omega_2^2 (r + \Delta r) \qquad (4\text{-}6)$$

From Equation 4-5

$$r = \frac{F_1}{M\omega_1^2}$$

Substituting into Equation 4-6

$$F_2 = M\omega_2^2 \left(\frac{F_1}{M\omega_1^2} + \Delta r \right)$$

$$F_2 = F_1 \left(\frac{\omega_2}{\omega_1} \right)^2 + M\omega_2^2 \, \Delta r$$

$$M = \frac{F_2 - F_1 \left(\frac{\omega_2}{\omega_1} \right)^2}{\omega_2^2 \, \Delta r}$$

Since $M = W/g$

$$W = g \left[\frac{F_2 - F_1 \left(\frac{\omega_2}{\omega_1} \right)^2}{\omega_2^2 \, \Delta r} \right] \qquad (4\text{-}7)$$

F_1 = first force read from strain gage link - lb

F_2 = second force read from strain gage link - lb

ω_1 = first angular velocity - rad/sec

ω_2 = second angular velocity - rad/sec

$$\omega = \frac{RPM\ (2\pi)}{60} = \frac{RPM}{9.549}$$

4.3 ERROR ANALYSIS--TWO-RADIUS METHOD

Rearranging Equation 4-7

$$W = \frac{g F_2}{\omega_2^2 \Delta r} - \frac{g F_1}{\omega_1^2 \Delta r}$$

Using the chain rule of partial differentiation

$$\Delta W = \frac{\partial W}{\partial F_1} \Delta F_1 + \frac{\partial W}{\partial F_2} \Delta F_2 + \frac{\partial W}{\partial \omega_1} \Delta \omega_1 + \frac{\partial W}{\partial \omega_2} \Delta \omega_2$$

$$\frac{\partial W}{\partial F_1} = \frac{-g}{\omega_1^2 \Delta r}$$

$$\frac{\partial W}{\partial F_2} = \frac{g}{\omega_2^2 \Delta r}$$

$$\frac{\partial W}{\partial \omega_1} = \frac{g F_1}{\omega_1^3 \Delta r}$$

$$\frac{\partial W}{\partial \omega_2} = \frac{-2g F_2}{\omega_2^3 \Delta r}$$

$$\Delta W = \frac{-g}{\omega_1^2 \Delta r} \Delta F_1 + \frac{g}{\omega_2^2 \Delta r} \Delta F_2 + \frac{2g F_1}{\omega_2^3 \Delta r} \Delta \omega_1 - \frac{2g F_2}{\omega_2^3 \Delta r} \Delta \omega_2$$

$$\Delta W = \frac{g F_1}{\omega_1^2 \Delta r} \times \left(\frac{2 \Delta \omega_1}{\omega_1} - \frac{\Delta F_1}{F_1} \right) + \frac{g F_2}{\omega_2^2 \Delta r} \times \left(\frac{\Delta F_2}{F_2} - \frac{2 \Delta \omega_2}{\omega_2} \right)$$

$$\Delta W = \frac{g}{\Delta r} \left[\frac{F_1}{\omega_1^2} \left(\pm e_{\omega_1} \pm e_{F_1} \right) + \frac{F_2}{\omega_2^2} \left(\pm e_{F_2} \pm e_{\omega_2} \right) \right] \qquad (4\text{-}8)$$

ΔW = error in weight - lb

e_{ω_i} = error in angular velocity

e_{F_i} = error in force

Based on Equation 4-8, a sample case follows. Assume $\Delta r = 0.5$ ft, $r_1 = 1.5$ ft, and $r_2 = 2.0$ ft

$F_1 = F_2 = 180$ lb nominally

$$F_1 = 180 = \frac{180}{32.2}\omega_1^2 (1.5); \omega_1^2 = \frac{32.2}{1.5}; \omega_1 = 4.62 \text{ rad/sec} = 44 \text{ rpm}$$

$$F_2 = 180 = \frac{180}{32.2}(\omega_2^2)(2); \omega_2^2 = \frac{32.2}{2.0}; \omega_2 = 4.025 \text{ rad/sec} = 38.5 \text{ rpm}$$

$$\Delta W = \frac{32.2}{0.5}\left[\frac{180(1.5)}{32.2}(0.00045 + 0.001) + \frac{180(2)}{32.2}(0.001 + 0.000515)\right]$$

$$\Delta W = 540 (\pm 0.00145) + 720 (\pm 0.001515)$$

$$\Delta W = 0.783 + 1.0908 = 1.8738 \text{ lb}$$

$$\Delta W = \pm 1.8738 \text{ lb}$$

$$\frac{\Delta W}{W} = \frac{1.8738}{180} = \pm 1.041\%$$

4.4 TESTS OF THE EFFECTIVENESS OF THE TWO-RADIUS METHOD

A test program to prove the effectiveness of the two-radius method of determining weight in a zero-g environment was recommended in a previous report (Reference 2-7). This recommendation was accepted, and a test apparatus was designed and constructed. The apparatus is shown mounted on

the centrifuge in Figure 4-3. The chair is mounted on rollers on all four corners as shown in Figure 4-4, so that the chair is free to move along a ray line. The chair is anchored to the centrifuge structure through a precision load cell with a capacity from zero to 500 lb. The load cell is attached to a bar which, in turn, is attached to the chair. The bar has two holes, 6 in. apart, that allow the chair to be moved a precise Δr along a ray line.

A strain gage readout device was mounted directly on the chair so that the entire load cell and readout system was contained on the rotating part of the centrifuge, thus eliminating the potential error of sending strain voltages through slip rings. The readout device was battery powered. A closed-circuit television camera was placed so that the null position of the strain-gage readout device could be monitored in the centrifuge control room. Figure 4-5 shows the readout device as seen on the control-room television monitor.

The angular velocity of the centrifuge is determined as follows: a pulse generator which generates 600 pulses/revolution is electrically connected to the centrifuge. The pulses are counted in an electronic counter where the count is divided by a time standard, and rpm is shown digitally.

A series of preliminary test runs were completed just prior to relinquishing use of the centrifuge to a high-priority test. Some difficulties were encountered with the readout of rpm which could not be resolved in the limited time available, and for this reason no meaningful data were obtained. The test procedure followed during these preliminary runs was as follows: the weight of the chair and all supporting structure was carefully determined during installation on the centrifuge, and again upon removal. The subjects, complete with headphones and ECG leads, were carefully weighed to the nearest hundredth of a pound. The subjects were placed in the chair (seat belts fastened, headphones and ECG leads connected) and were given instructions to keep arms and legs in the same position during the runs. The load cell readout device was checked for zero calibration and was then set to an equivalent force of 400 lb. The centrifuge was started and the

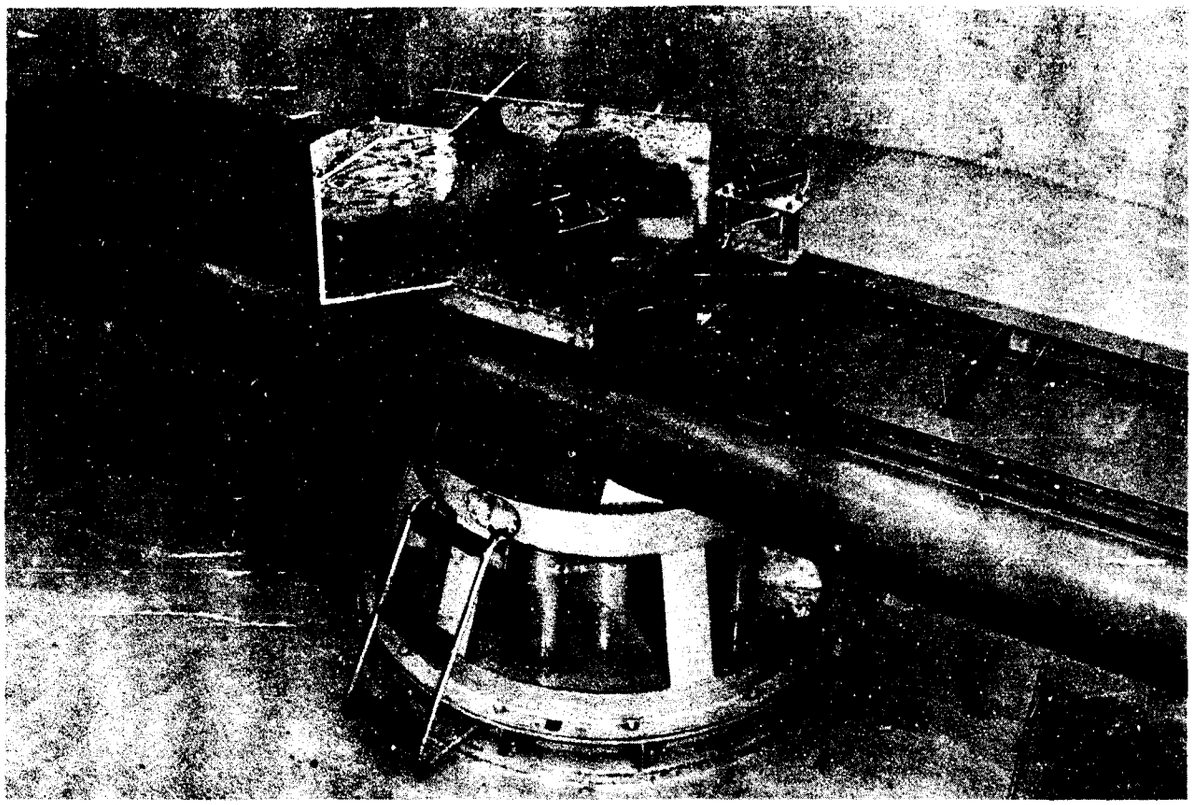


Figure 4-3. Weight Determination Apparatus Mounted on Centrifuge

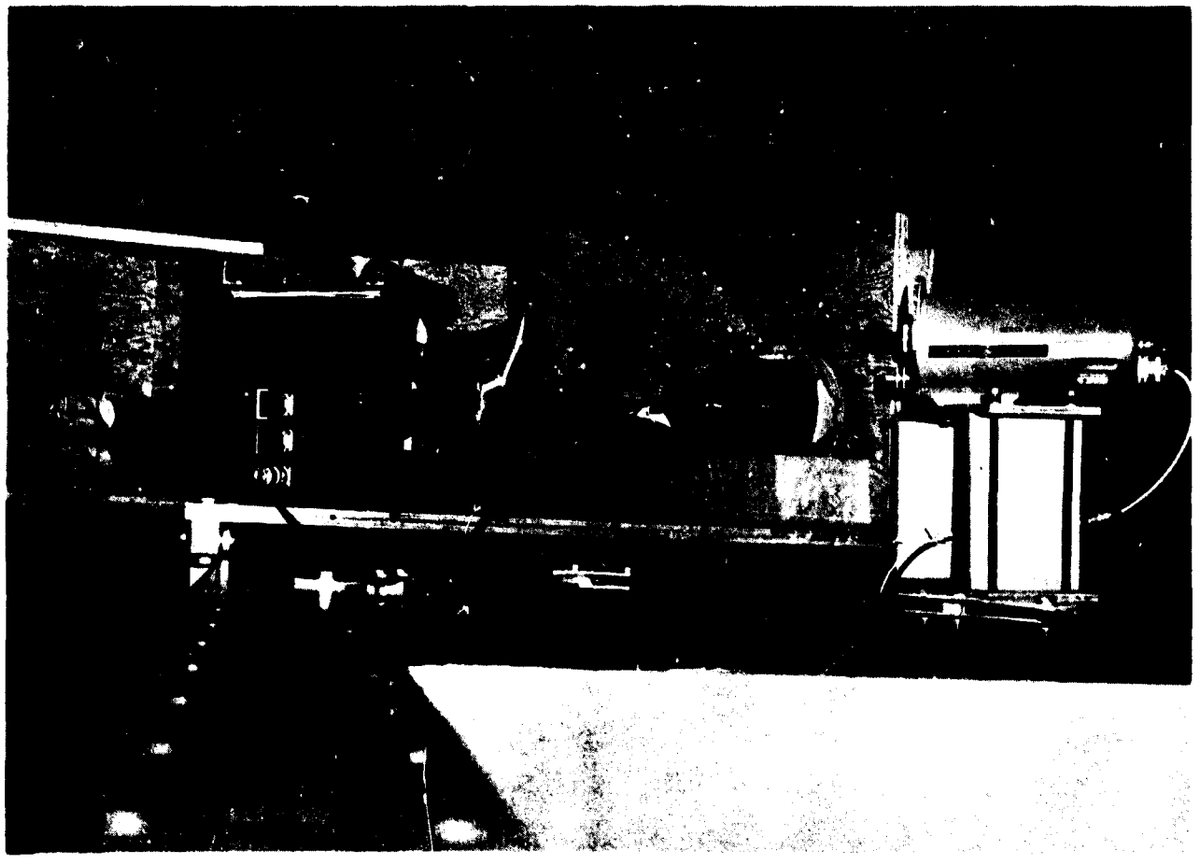


Figure 4-4. Weight Determination Apparatus Showing Rollers and Load Cell

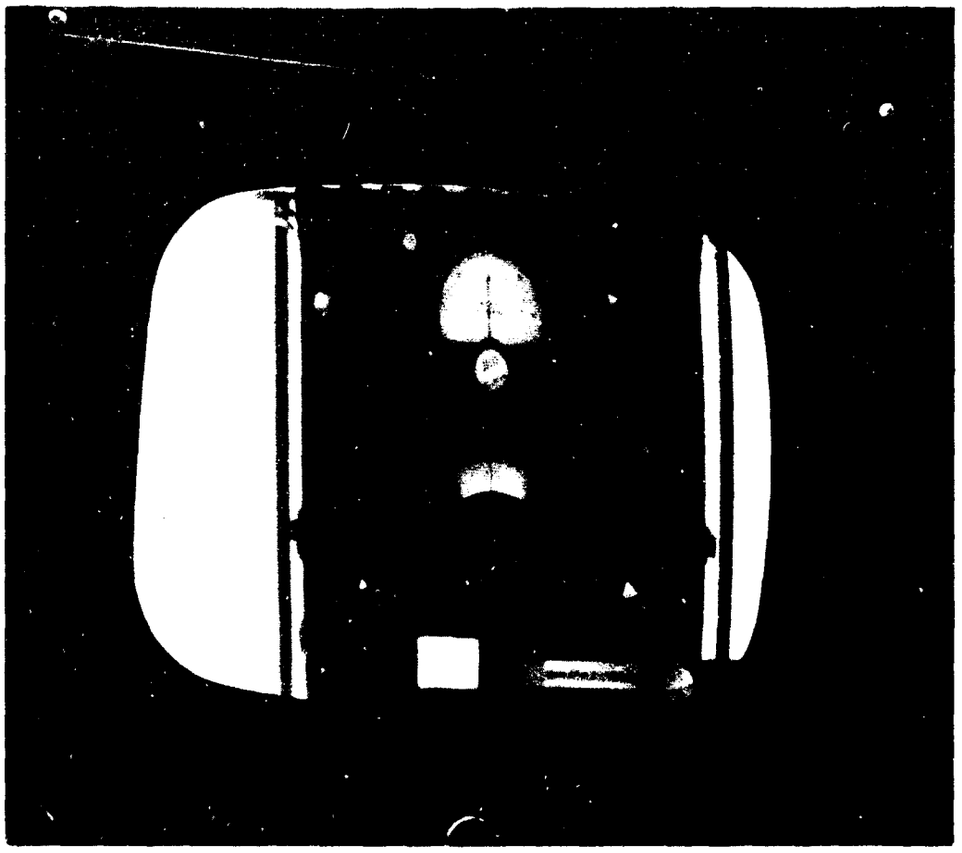


Figure 4-5. Weight Determination Apparatus Force Read-out as Seen on Television Monitor

force readout device was nulled by modulating the rpm of the centrifuge. The rpm was recorded and the centrifuge was brought to a stop. The radius was then changed by Δr with the subject remaining in the chair. The process was then repeated at the new radius.

The above test procedure was used to apply the same centrifugal force to the subject at each radius, which would imply that the major organs of the body should seek similar positions, thus lessening the potential error. The weight was then calculated from the following expression:

$$W = gF \left[\frac{1 - \left(\frac{\omega_2}{\omega_1} \right)^2}{\omega_2^2 \, \Delta r} \right]$$

Additional runs with this apparatus are planned for the near future.

4.5 REFERENCES

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Section V
CONSPECTUS OF BED-REST RESEARCH

There have been a number of good general reviews and specialized comments on the biomedical implications of null gravity. Probably the most comprehensive reviews are those of Wunder (Reference 5-1) and McCally and Lawton (Reference 5-2). This conspectus contains the salient generalizations from a series of studies in which bed rest was used as an analog of null gravity.

5.1 EFFECTS OF BED REST

When a healthy man is placed at bed rest, the body promptly adjusts to the lessened activity and the absence of gravitational stress by the following:

1. A negative nitrogen balance--Nitrogen excretion begins to increase toward the end of the first week of bed rest, reaching its peak during the first half of the second week, and remaining at an elevated level during recumbency (References 5-3 through 5-5).
2. An increased excretion of calcium and phosphorus in the urine and feces reaching a peak 2 to 3 times normal levels during the fourth or fifth week of bed rest (References 5-3 through 5-7).
3. A lowering of creatine tolerance (Reference 5-3).
4. An increased excretion of sulfur, sodium, and potassium--Sulfur is excreted in the urine in close correlation with urinary nitrogen. Sodium and potassium increases are small and variable (References 5-3 through 5-5).
5. A mild diuresis averaging 200 to 300 cc/day (References 5-3 through 5-6).
6. A decrease in plasma volume, blood volume, and extracellular fluid (References 5-3, 5-4, 5-5, 5-8, and 5-9).
7. An increase in resting pulse rate (References 5-3 through 5-6).
8. A loss of tilt-table tolerance--Tolerance is manifested by an increased heart rate, decreased systolic blood pressure, narrowed pulse pressure, and clinical appearance of impending syncope and syncope (References 5-3 through 5-7).

9. A development of petechiae over the feet and legs after tilting (Reference 5-3).
10. A decreased work tolerance as evidenced by rapid exhaustion, elevated heart rates, decreased ability of the cardiovascular-respiratory system to deliver O_2 at the pre-bed-rest levels (References 5-3 through 5-7).
11. A slight decrease in muscular tone, strength, and circumference of extremities (References 5-3 through 5-7).
12. A reduction in BMR by 6 to 7% after 6 to 7 weeks (References 5-3 and 5-6).

Other effects have been reported but these are the best documented.

5.2 MINIMIZING BED-REST EFFECTS

Since these alterations are undesirable, several attempts have been made to modify or to prevent their occurrence. Practically all attempts have been directed toward the cardiovascular, neuromuscular, and skeletal systems, and they have received their direction from studies that have shown the following:

1. Wrapping the legs with an ace bandage before tilting provides some protection against orthostatic intolerance (Reference 5-3).
2. Oscillating beds decrease the deleterious effects of bed rest (Reference 5-4).
3. Supine exercise reduces loss of work tolerance but does not affect orthostatic tolerance (Reference 5-7).
4. Quiet sitting in a chair 8 hours/day may reduce orthostatic intolerance but not the loss of work tolerance (References 5-7 and 5-12).
5. Sitting exercise may reduce both orthostatic intolerance and loss of work tolerance (Reference 5-7).
6. Increased venous tone is seen in tilted normal subjects but is decreased in subjects with postural hypotension (Reference 5-10).

Consideration of these factors suggests:

1. Improvement of venous tone, and thereby improvement in central venous pressure with consequent increased cardiac output, should help prevent orthostatic intolerance.

2. Exercise alone probably does not prevent orthostatic hypotension but does maintain work capacity.

3. Acceleration fields alone do not prevent loss of work capacity but probably do prevent orthostasis.

Venous pooling can be prevented by wrapping the legs with ace bandages (Reference 5-3). The legs seem to be more important than the arms. Other methods of preventing venous pooling are directed either at increasing the basic venomotor tone, such as by positive pressure breathing, pressure cuffs, and negative pressure boot, or at prevention of loss in muscle tone (References 5-11 and 5-13). Loss of muscular tone and work capacity can probably be prevented by isotonic or isometric exercises.

Prevention of orthostatic intolerance, on the other hand, has been based on the generation of forces designed to maintain continued cardiovascular tone, such as the use of various forms of accelerative stress. The earliest approach to the problem was the oscillating bed. Since that time, the short-radius centrifuge and the trampoline-shuttle (Reference 5-14) have been proposed and are being investigated for use in orbital laboratories.

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Section VI
RECONDITIONING REGIMEN

The purpose of this pilot experiment was the study of the influence of periodic centrifugation on the physiological disturbances associated with 41 days of recumbency. The investigation was carried out in the biodynamic ward during 20 days of bed rest (deconditioning); 16 days of bed rest with periodic rides on a short-radius (4.5 ft) centrifuge; 5 days of bed rest, centrifugation, and physical exercise; and a 10-day recovery period. From the 21st to the 41st day, the subjects rode the centrifuge four times each day; the duration of each ride was 7.5 min. The level of acceleration applied was +1 g_z for one group of two subjects and +4 g_z for the other group of three subjects.

The reconditioning regimen was arrived at by parameterization. Maintenance of cardiovascular tone appears to be a function of the hydrostatic pressure in the arterial and venous system of the legs and the duration of this pressure. Birkhead, et al.(Reference 5-7), for example, reports that 8 hours/day of quiet sitting by subjects at bed rest largely prevents orthostatic intolerance. Under this condition, the hydrostatic pressure in the veins of the legs was about 67 mm Hg. When this pressure is multiplied by the duration of this pressure in hours, a parameter of 533 mm Hg-hours is established. If the additional assumption is made that pressure and time are of equal weight, and therefore interchangeable, 134 mm Hg for 4 hours or 268 mm Hg for 2 hours would be adequate for the maintenance of cardiovascular tone during recumbency. Limitations of these assumptions are recognized; however, parameterization was used in this experiment as the basis for establishing the duration, frequency, and magnitude of exposure to acceleration during reconditioning.

6.1 METHOD

The measures followed and the experimental plan of the test are presented in the following paragraphs.

6.1.1 Subjects

Five normal, healthy men were studied while on a constant diet during 41 days of experimentation. All were paid volunteers. Prior to the study, the subjects were thoroughly briefed on the nature of the experiment, probable risks, and the steps taken to ensure their health and welfare. During the course of the experiment, they were informed of any changes, and at the conclusion of the study, they were told of the findings and given the final technical report to read. The subjects were free to withdraw from the experiment at any time. Admitting history, physical examination, Master's ECG, urinalysis, and blood analysis of each were normal. Physical characteristics of the subjects are shown in Table 6-I. As a group, they had over 1,000 rides on the centrifuge.

Table 6-I
PHYSICAL CHARACTERISTICS OF SUBJECTS

GROUP	SUBJECT	AGE	HEIGHT (cm)	WEIGHT (kg)	PLASMA VOLUME LEAN MASS (ml/kg)
+1 g_z	BW	23	183.0	64.0	64.3
	NK	28	180.0	78.4	51.6
+4 g_z	LB	25	167.5	60.7	44.8
	GK	22	145.0	91.8	42.1
	BS	22	145.5	73.7	45.8

The subjects were placed on a diet calculated to be 2,100 kcal. Average daily calcium intake was calculated to be between 0.6 gm and 1.0 gm. The basic meal plan is shown in Table 6-II.

6.1.2 Intercurrent Measures

Table 6-III lists the functional, diagnostic, and monitoring tests performed during the program. These can be further subdivided into baseline studies made prior to and after the experiment and the intercurrent measures. The table gives the dates of each administration of the tests. Tests administered once, for example, VDRL, are not shown in the table.

The tilt-table test was used to measure the functional reserve of the cardiovascular system. The subjects, suspended in a modified parachute harness, were tilted to 90° with feet downward for 20 min (unless syncope intervened). With the subjects in this position, heart rate and blood pressure readings were obtained once a minute. ECG's were taken before, during, and following tilting. This test was performed at the same time of day (2030 hours) and under relatively constant temperature conditions (70°F). All tilt-table tests were conducted by the same physician.

To determine tolerance to positive acceleration, bioassay runs were conducted on the centrifuge. The distance from heart level to center of rotation was 172 in. Each run was conducted at a rate of onset and decay of 0.2 g/sec, and the peak acceleration was maintained for 15 sec. During the runs, heart rate and ECG were monitored. Blackout, or loss of tolerance, was at the level of acceleration at which central and peripheral vision were lost.

The treadmill test of exercise tolerance consisted of walking at a speed of 3.3 mph, at a grade of 0%, 2%, 4%, 6%, and so forth, during each following minute. Cardiovascular response to increasing metabolic demands was monitored by measuring heart rate and ECG during the second half of each minute. The exercise tolerance test was terminated at heart rates of 170 beats/min. The time required to reach this heart rate was defined as tolerance threshold.

Table 6-II

BASIC MEAL PLAN

Breakfast

1 serving fruit
1 serving cereal with sugar
4 oz nonfat milk
1 egg
1 slice white enriched toast with margarine
coffee
sugar

Mid-Morning

1 serving fruit

Noon Meal

1 serving fish, poultry, or meat
1 serving starchy vegetable
margarine
1 serving cooked vegetable
1 serving raw vegetable
salad dressing
1 serving fruit
coffee
sugar

Mid-Afternoon

1 serving ritz crackers
1 serving peanut butter

Evening Meal

1 serving fish, poultry, or meat
1 serving starchy vegetable
1 serving cooked vegetable
1 serving raw vegetable
salad dressing
8 oz whole milk
1 serving fruit
coffee
sugar

Bedtime

1 serving graham crackers

The routine Master's two-step test with a 12-lead ECG was taken in the conventional manner. The results of this test were analyzed by a consulting cardiologist.

Tests of respiratory function included maximum breathing capacity, tidal volume, inspiratory capacity and expiratory reserve, vital capacity, and timed vital capacity. These functions were measured with the subjects in the supine position.

Urine and blood samples were analyzed in a conventional manner.* Blood and plasma volume determinations were made by the Evans blue (T-1824) method. Hematocrits were corrected by allowing 4.0% for the percent of the observed cell volume of plasma trapped between red cells. A dye standard was prepared for each lot of dye used for injection. Both plasma and blood volumes were calculated.

Body compostion was determined on the basis of a human-body volumeter and formulae developed by Allen (Reference 6-1) of the USAF School of Aerospace Medicine. Both lean body mass and fat were calculated.

Girth of the upper arms, the thighs, and the calves were measured at predetermined positions with a tape measure. Measurements were taken with the subject in the supine position.

Monitoring tests, shown in Table 6-III, followed hospital ward routine, and the results were recorded by the nurse on each of the three 8-hour shifts. Medical summaries, prepared by the duty nurse and augmented by the experimenters, included subject reaction to the conditions of the experiment and their attitudes toward each other and the staff.

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*Diagnostic tests were performed by Bio-Science Laboratories, Los Angeles, California

Table 6-III

BASELINE AND INTERCURRENT MEASURES

TESTS	DATE OF DETERMINATION							
FUNCTIONAL								
Orthostatic tolerance	B-1*	-	T-20	T-25	T-30	T-35	T-41	BR-10
Acceleration tolerance	B-1	-	-	-	-	-	-	BR-3
Exercise tolerance	B-1	-	-	-	-	-	-	BR-2
Master's exercise response	B-1	-	-	-	-	-	-	BR-3
Respiratory response	T-1	-	T-20	T-27	-	T-35	T-41	BR-3
DIAGNOSTIC								
Protein-bound iodine	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Calcium	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Phosphorus	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Electrolytes (Na, K, Cl, HCO_3)	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
CBC	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Plasma and blood volume	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Urinalysis (sugar, acetone, protein, pH, microscopic, specific gravity)	T-1	T-8	-	T-21	T-31	T-36	BR-1	BR-10
Calcium	T-1	-	T-15	T-21	T-31	T-36	BR-1	BR-10
Phosphorus	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Creatinine	T-1	-	-	T-21	T-31	T-36	BR-1	BR-10
Body weight	B-1	-	T-16	T-24	T-34	-	T-41	BR-2
Body composition	B-1	-	-	-	-	-	-	BR-2
Circumference of limbs	T-1	T-9	T-20	T-27	T-34	-	T-41	BR-2
MONITORING								
Blood pressure	Daily							
Temperature								
Heart rate								
Respiratory rate								
Fluid intake/output (24 hours)								
Medical summary								

*B = Baseline (B-1 = 10/5/65)
T = Bed Rest (T-1 = 10/6/65)
BR = Baseline-Recovery (BR-1 = 11/16/65)

6.1.3 Experimental Plan

The parameter and protocol followed in this study are shown in Table 6-IV. The study was divided into three experimental periods and one recovery period. During the entire 41 days of experimentation, the subjects were at bed rest. The only restriction placed on their movements in bed was that the long axis of the cardiovascular system be maintained in the horizontal position. Three nurses, each working the same 8-hour shift, rigorously monitored the subjects and administered routine "bed-fast" nursing care.

Table 6-IV
EXPERIMENTAL PLAN

PARAMETER	$+g_z$ GROUP	$+4\ g_z$ GROUP
g-Time	0.5 g-hrs	2.0 g-hrs
Effective* hydrostatic pressure	44 mm Hg	177 mm Hg
No. of subjects	2	3
Heart-to-foot g gradient	219%	
Dose rate	Four 7.5-min rides/8-hr day (0830-1530) - 2 hr between rides	
Protocol	1 day baseline (B-1)	
	20 days bed rest (T-1 to T-20)	
	16 days bed rest + centrifuge (T-21 to T-36)	
	5 days bed rest + g + exercise (T-37 to T-41)	
	10 days baseline + recovery (BR-1 to BR-10)	

*At the feet

The first 20 days of the experiment comprised the deconditioning period. Periodic centrifugation was added as a reconditioning regimen during the second period. During this and the following experimental period, the subjects were transferred from their beds to the centrifuge and returned to bed by means of a net hammock and traveling hoist. Figure 6-1 shows a transfer operation. Exercise was added to periodic centrifugation during the third experimental period. The purpose of the exercise was to restore muscle tone and to gain some clinical insight for the subsequent program. The exercise consisted of pushing with the ball of one foot against a scale. It was performed four times each day, immediately after centrifugation, while the subjects were in bed. Figure 6-2 shows a subject performing the required exercise. The recovery period lasted 10 days. During the first three days, the subjects remained in the ward shown in Figure 6-3 and participated in the postexperimental tests. On the fourth day, all subjects returned home, but reported by phone periodically until the tenth day and a final physical examination. They were discharged on the 51st day of the experiment.

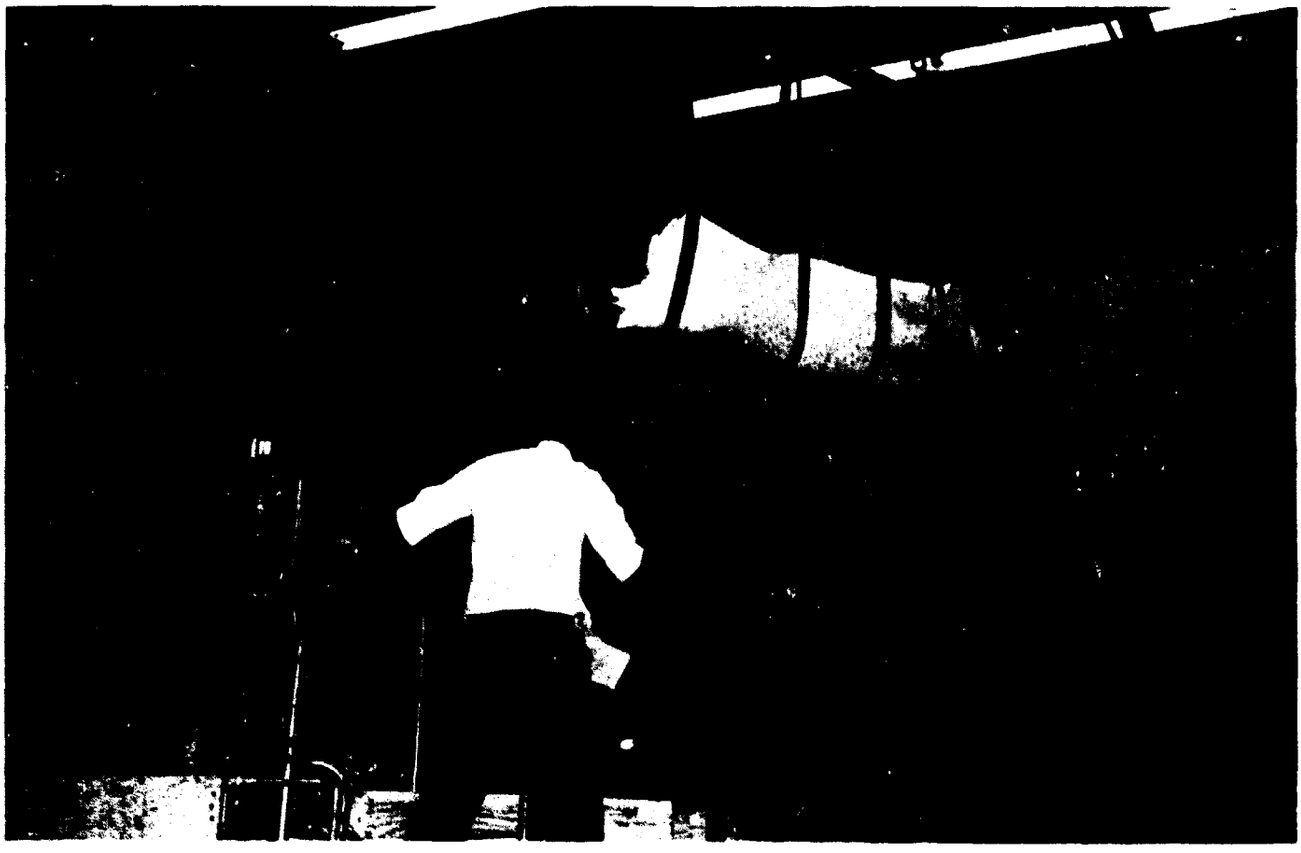


Figure 6-1. Transportation From Bed to Centrifuge

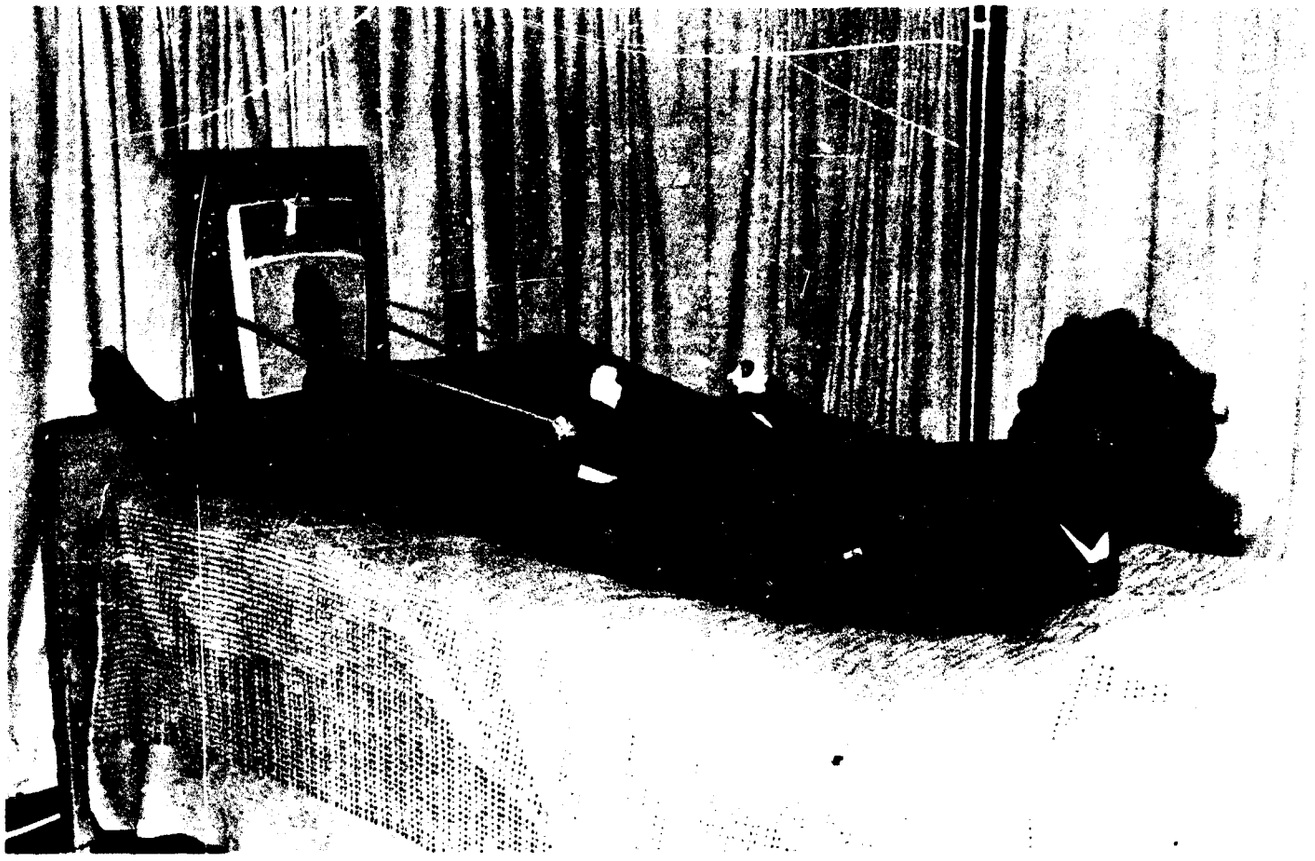


Figure 6-2. Physical Exercise

The physical aspects of reconditioning are shown in Figure 6-4. The radius of the centrifuge was 4.5 ft. The graphic inset in the figure gives the acceleration at any point on the body for four different angular velocities. A platform with two seats was mounted on the Douglas human centrifuge. Figure 6-5 shows the positions occupied by the subjects while riding the centrifuge. The dual seating arrangement minimized cost.

The reconditioning regimen on the centrifuge was designed to keep constant the duration, frequency, and rate of exposure to acceleration, whereas the magnitude of acceleration was allowed to vary over a range of 1 to 4 g_z units. For the first day and a half, reconditioning rides for all subjects were at the level of +1 g_z. After this period, the five subjects were split into a +1 g_z and a +4 g_z group. The former remained at this level of acceleration for the succeeding 21 days of the experiment. The latter group were exposed to successively high levels of acceleration every 1-1/2 days until they reached +4 g_z on the third day. Since the heart-to-foot

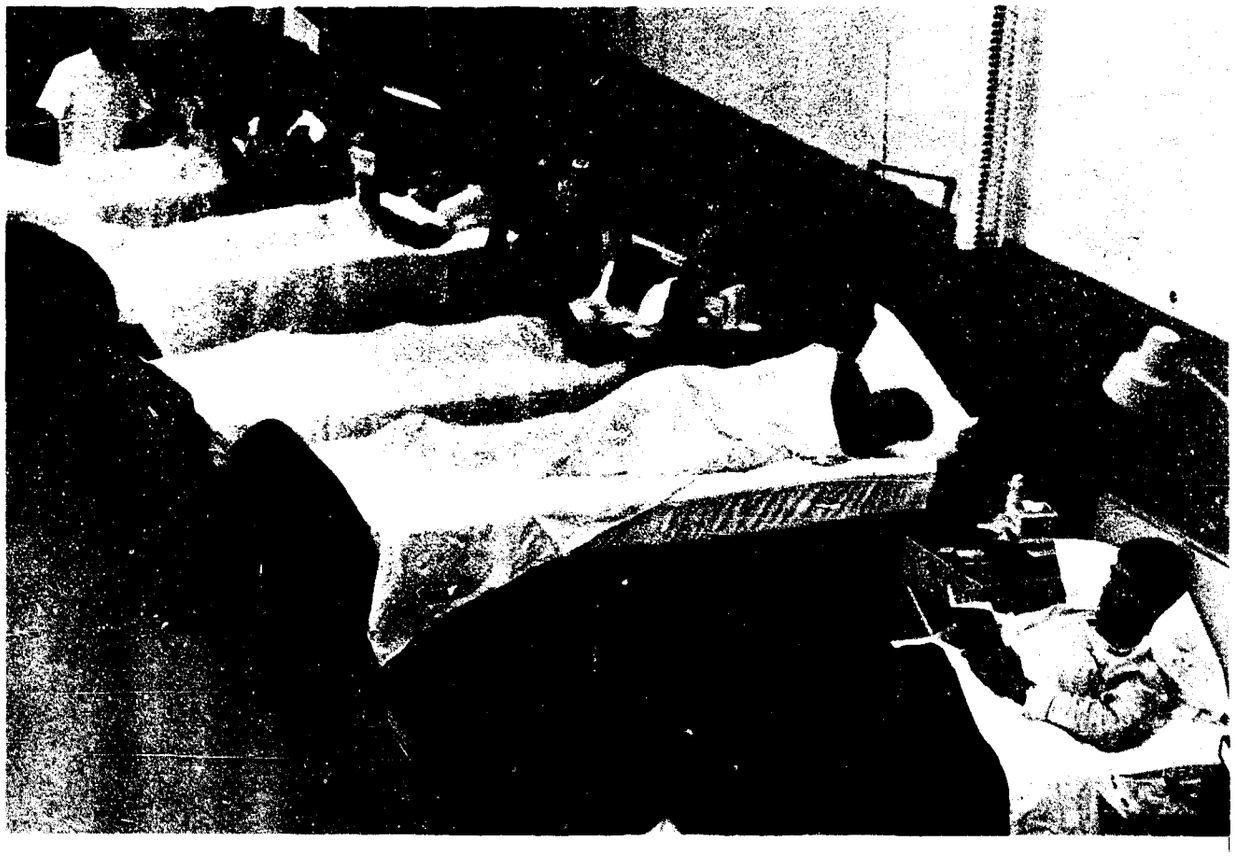


Figure 6-3. Biodynamic Ward

acceleration gradient was 219%, the levels of acceleration were referenced to the subjects' feet*. Calculated hydrostatic pressure at the foot in the low-acceleration group was 44 mm Hg, and 117 mm Hg in the high-acceleration group.

Duration of a ride on the centrifuge was 7.5 min and the frequency of exposure was four times a day; both were arrived at on the basis of parameterization of pressure and time. The +1 g_z group experienced 0.5 g-hours every 24 hours, while the +4 g_z group rode 2.0 g-hours. All reconditi- ~ rides on the -~-t-ifuge took place between 0830 and 1530 hours. The subjects followed a r.. dule that called for 2 hours between successive rides and 6 hours between the start of the first and last rides of the day.

*Acceleration gradient is equal to the acceleration at the feet (g) minus the acceleration at the heart (g) divided by the acceleration (g) at the heart. Multiplication by 100 converts this expression to percentage and represents the physical gradient applied to the subject.

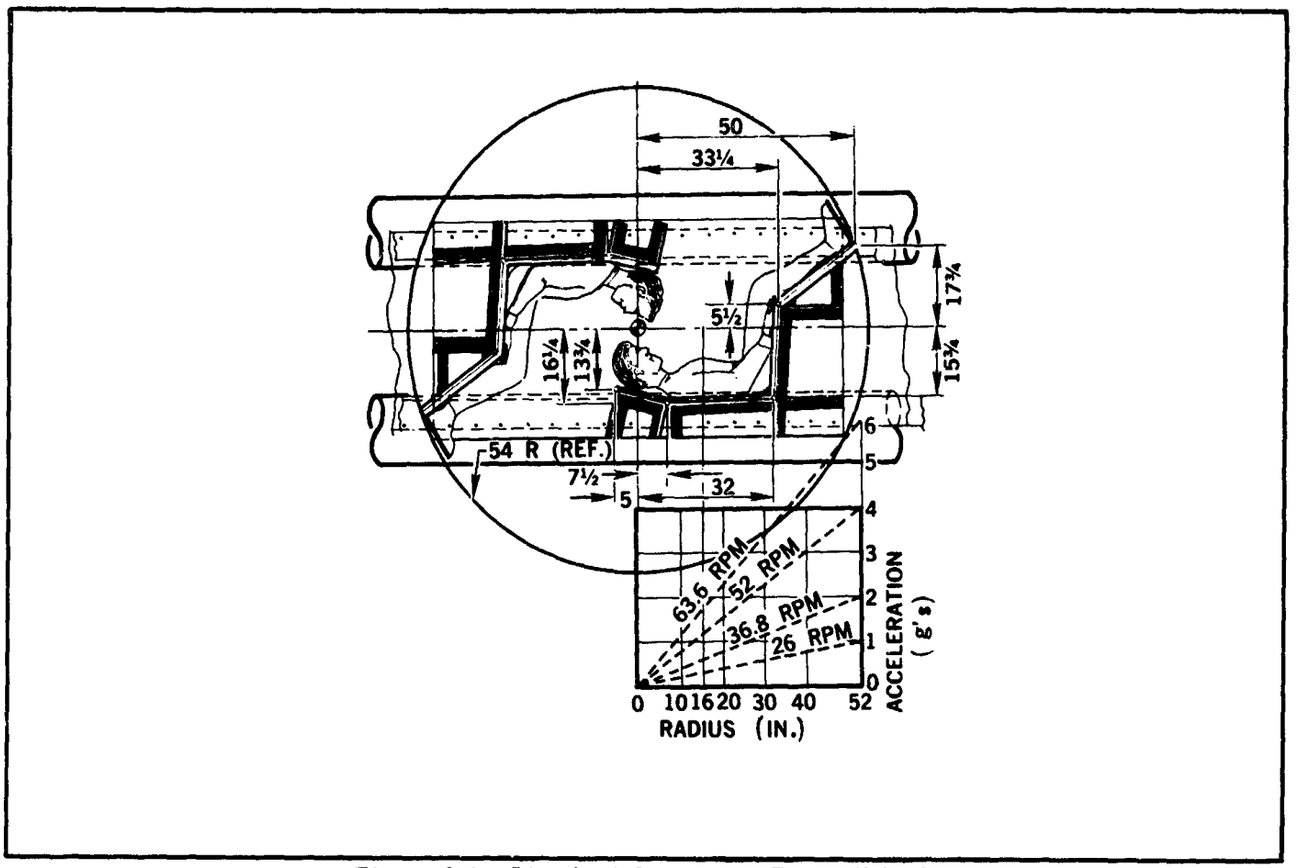


Figure 6-4. Physical Aspects of Reconditioning

6.2 RESULTS

A detailed discussion of the functional, diagnostic, and monitoring tests is presented below.

6.2.1 Functional Tests

The results of the tilt-table tests of orthostatic tolerance are summarized numerically in Table 6-V and are presented graphically in Figure 6-6 for each subject. On B-1, the day prior to the beginning of the experiment, all subjects were tested on the tilt table. All subjects tolerated the procedure well and reported feeling alert during the entire test. Slight pallor was the only symptom noted. The expected increase in heart rate and a narrowing of pulse pressure were noted; however, neither of these findings was marked.

Twenty days of bed rest produced marked changes in orthostatic tolerance. Four subjects developed syncope as evidenced by narrowed pulse

Table 6-V

DURATION, HEART RATE, PULSE PRESSURE, AND MEAN ARTERIAL PRESSURE DURING TILT

GROUP	SUBJECT		B-1				T-20				
			Time*	$\int_1^{20}$ Heart Rate** dt	$\int_1^{20}$ Pulse Pressure*** dt	M.A.P.	Time	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.	T-I
	BW		20	1812	324	100.1	16	1624	341	103.6	6
$+1g_z$		Mean		91	16			102	21		
	NK		20	1924	482	104.9	20	2518	203	92.7	7
		Mean		96	24			126	11		
	LB		20	1480	365	106.6	13	1256	204	102.7	
		Mean		75	18			96	16		
$+4g_z$	GK		20	1568	446	114.0	13	1201	③	110.5②	
		Mean		78	21			93	10		
	BS		20	1543	536	97.3	12	1070	205	90.4	
		Mean		78	26			90	16		

*Min.
**Beats
***mm Hg
M.A.P. = Mean Arterial Pressure (mm Hg)

① For first 12 min. only

② For

A

IME OF DETERMINATION

	T-25				T-30				T-35			
T. P.	Time	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.	Tim	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.	Time	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.
6	20	2684	527	110.6	2(	2830	258	100.6	20	2605	220	10
		130	26			140	13			130	11	
7	20	2407	253	103.2	8	852	24 ②	106.7 ②	20	2230	167	10
		121	12			105	8			112	8	
(	20	1820	430	112.7	2(	2068	534	108.3	20	2082	282	11
		91	22			103	27			104	14	
5 ②	20	2037	③	107.5	1(	1574	85	106.9	20	2125	102	1(
		103	11			112	6			106	6	
4	20	1865	215	108.9	2(	1924	175	101.1	20	1818	288	1(
		94	11			96	9			91	14	

'or first 3 min only

③ Missing dreclude pulse integration

2

B

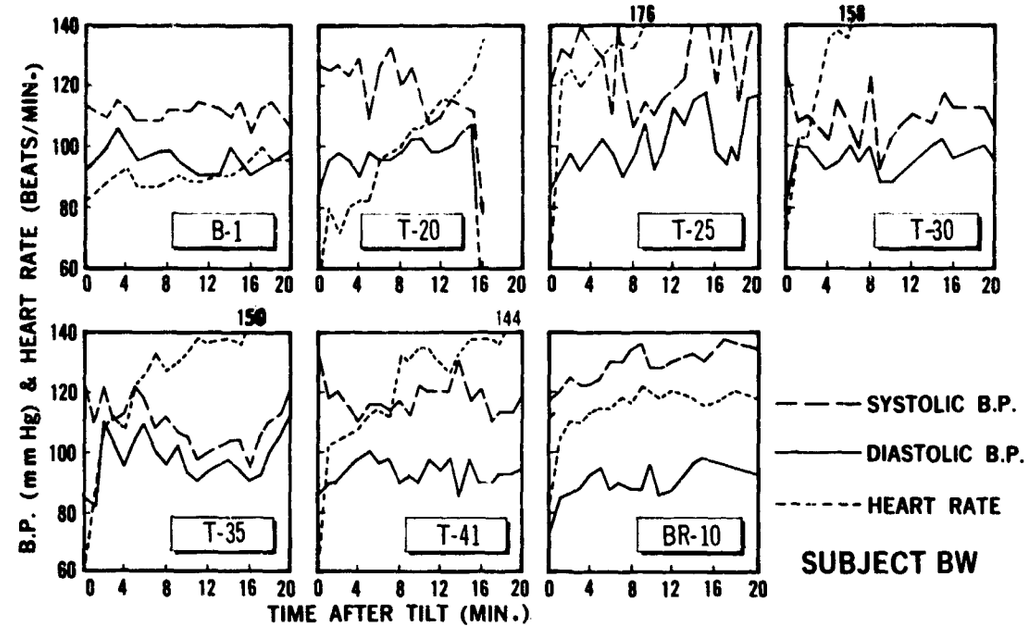
T-35			T-41				BR-10			
$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.	Time	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.	Time	$\int_1^{20}$ H.R. dt	$\int_1^{20}$ P.P. dt	M.A.P.
2605	220	102.3	20	2498	471	101.3	20	2322	772	99.2
130	11			126	24			116	38	
2230	167	105.3	20	2701	202	97.5	20	2108	469	94.2
112	8			135	9			105	24	
2082	282	112.1	20	2021	222	111.3	20	2128	456	98.1
104	14			102	11			106	23	
2125	102	108.4	20	1984	214	108.8	20	1816	432	105.9
106	6			99	11			91	22	
1818	288	100.6	20	2030	374	98.8	20	1910	410	92.0
91	14			103	19			96	21	

3 C

Figure 6-5. Dual Seating Arrangement

pressure, elevated heart rate, and clinical appearance. They were observed to have extreme pallor and cool moist skin, and they reported symptoms such as nausea and tingling of their extremities. The average time at 90° tilt, prior to syncope, was 13.8 min. Several minutes prior to the termination of the test, the pulse pressure narrowed markedly. Heart rate was generally elevated, although in one case bradycardia developed prior to syncope. One subject, although he did not faint, did develop moderate pallor, his extremities were cold, and he felt weak and nauseated. This period of bed rest brought about a deterioration in the mechanisms essential for adequate circulation in the erect body position.

On the 25th day of recumbency, and after 5 days of centrifugation, the subjects were again tilted, but no syncope developed. Mild to moderate pallor developed, but all subjects stated that they felt alert throughout the procedure. A difference between the +1 g_z group (Figure 6-6, Subjects BW and NK) and the +4 g_z group (Subjects LB, GK, and BS) was apparent.



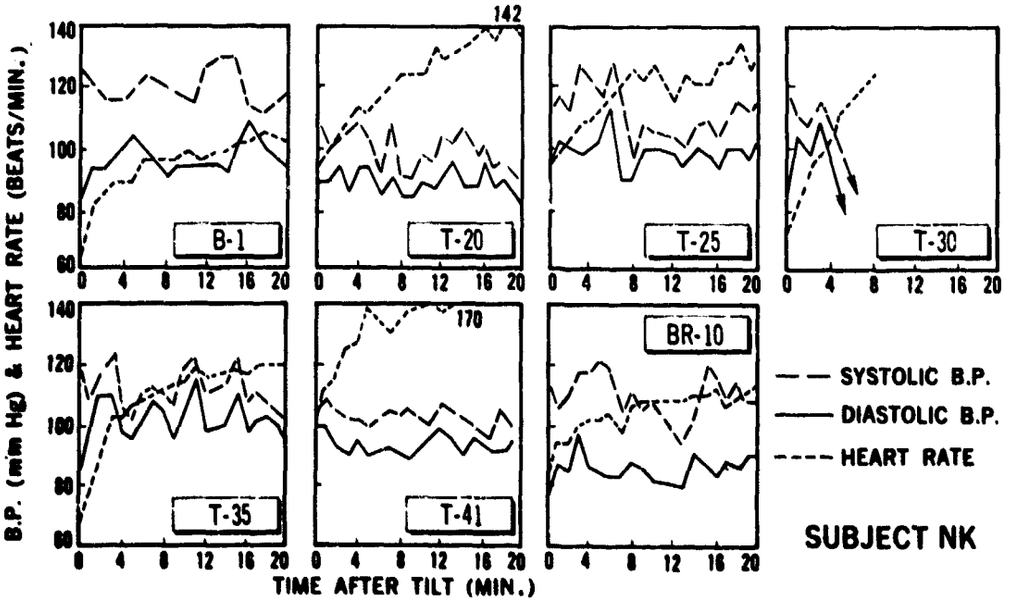
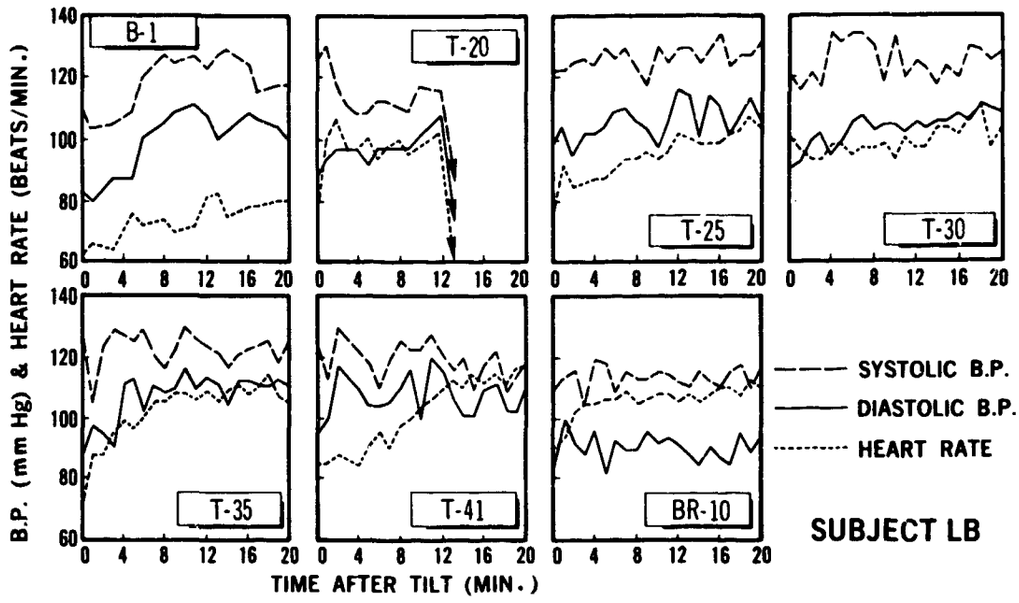


Figure 6-6. Orthostatic Tolerance for Each Subject



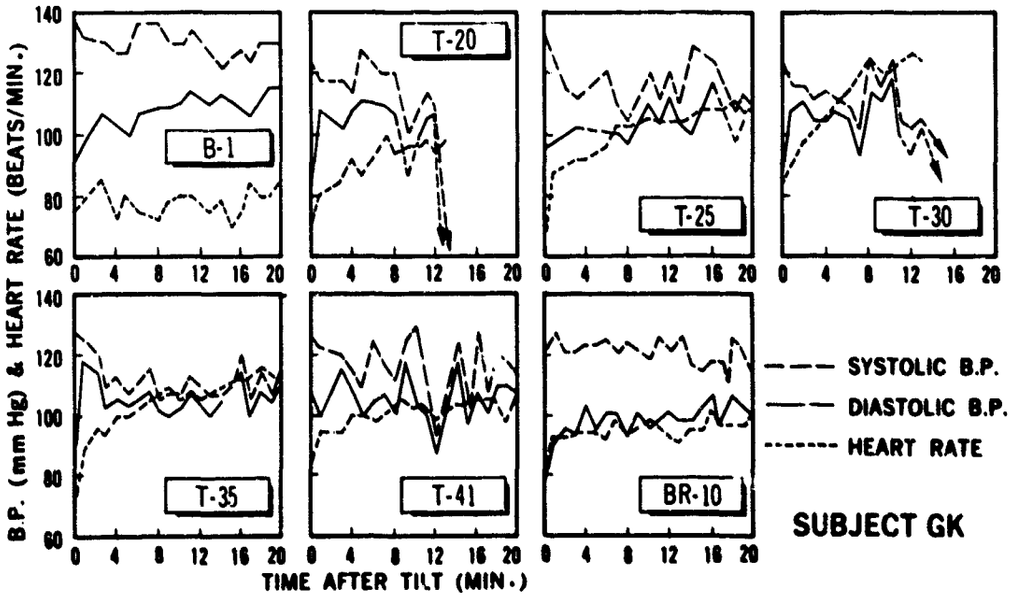


Figure 6-6. (Continued)

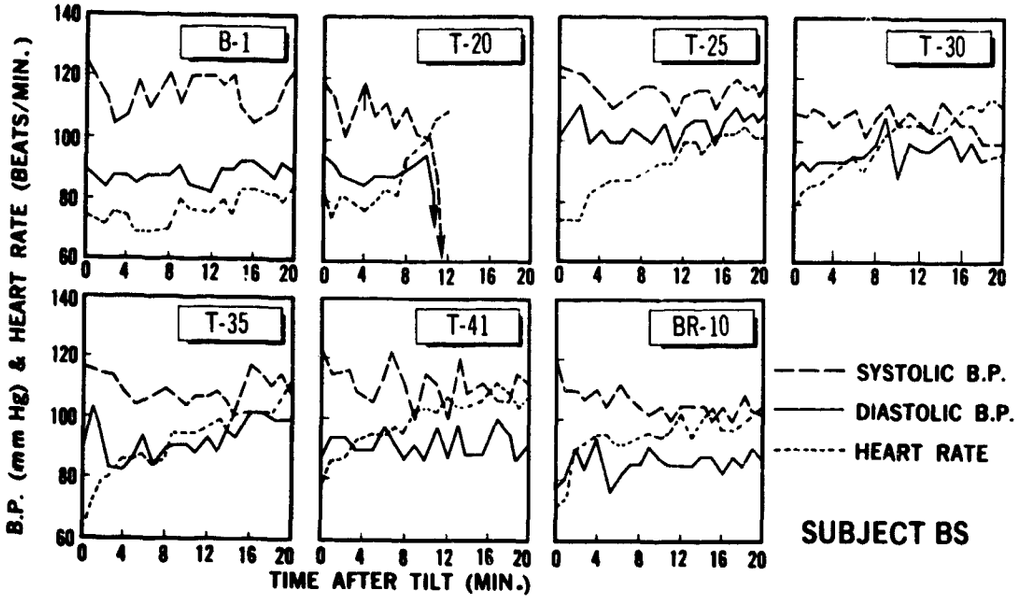


Figure 6-6. (Concluded)

The former showed lability of blood pressure and heart rate as judged by visual analysis of the orthostatic-tolerance curves. The latter group showed more stability in these measures.

After 30 days of recumbency and 10 days of centrifugation, two subjects, one in the +1 g_z group and one in the +4 g_z group, developed syncope during tilting after 8 and 14 min, respectively. The other three subjects showed further narrowing of pulse pressure and tachycardia when compared to the previous test. The difference in heart rate between the two groups was more marked than that on the previous tilt-table test. Moderate to marked pallor was noted in all subjects. The two subjects developing syncope stated they felt especially tired that day. Loss of muscle tonus could have influenced the results obtained at that time.

After 35 days of bed rest and 15 days of centrigugation, the subjects showed no signs of syncope on tilting. The subjects reported that they generally felt more rested than on the previous day of tilt. Subjects who showed

evidence of low pulse pressure (less than 10 mm Hg) reported that they felt alert and clear. The chief difference between the +1 g_z and the +4 g_z groups was in heart rate, the +4 g_z group maintaining the lower rate.

Tilt-table responses after 41 days of recumbency, 16 days of centrifugation, and 5 days of centrifugation and isometric exercise showed a slight tendency toward widening of the pulse pressure, although the pattern of tachycardia remained. Less pallor was noted as compared to the previous tilt-table tests. No syncope occurred.

The final tilt test, 10 days after termination of the bed-rest portion of the experiment, showed widening of pulse pressure toward pre-experimental limits, definite lowering of heart rate, and no presyncopal symptoms.

During all tilt-table tests, the dorsalis pedis and maleolar pulsations were checked and found to be strong.

Deterioration in the ability of the subjects to maintain the upright position produced by recumbency was largely prevented by periodic centrifugation. Subjects receiving +4 g_z four times each day showed less lability in blood pressure and heart rate than did the subjects exposed to +1 g_z.

Tolerance to positive acceleration was measured before and immediately after the 41-day experimental period. A summary of the results of this test is shown in Table 6-VI. Tolerance was measured using the standard bioassay technique and a slow rate of onset of acceleration (0.2 g/sec) at a radius of 172 in. (20% heart-to-foot gradient). The results are as follows for each subject during the postexperimental rides:

1. BW - +4.0 g_z -- Run aborted because of questionable prolongation of P-R interval on ECG (repeat ECG's were normal). Physical examination revealed minimal edema of feet and scattered petechiae.
2. NK - +4.5 g_z -- Lost peripheral lights. Minimal edema of feet and scattered petechiae.
3. LB - +5.0 g_z -- Felt as though a shield was lowering over eyes. Breathing became difficult, and much pressure was noted in lower extremities. The feet were quite red.
4. GK - +5.0 g_z -- Lights appeared hazy, extreme pressure in coccygeal region and neck, breathing labored. Transient loss of equilibrium at end of run.

Table 6-VI

EXERCISE AND ACCELERATION TOLERANCE

GROUP	SUBJECT	TIME + % GRADE TO HEART RATE OF 170 BEATS/MIN.						+ g_z TOLERANCE*	
		B-1		BR-2		BR-10		Before BR-3	
+1 g_z	BW	5	8	3	4	6	10	4.5	4.0 †
	NK	5●	8●	7	12	9	16	3.5	4.5
+4 g_z	LB	6	10	5	8	5	10	---	5.0
	GK	7	12	4	6	6	8	---	5.0
	BS	8	14	6	10	7	12	5,0	4.8

* Entries are in + g_z units at heart level

† Terminated because of questionable prolongation of P-R interval

● Power failure at heart rate of 162 beats/min

5. BS - +4.8 g_z -- Haze over all lights, pressure in legs, difficulty in breathing, and "dizziness" at end of run. Physical examination revealed minimal edema and scattered petechiae of feet.

These data show no appreciable drop in tolerance for positive acceleration.

A comparison of the pre-experimental and postexperimental responses to gradually increasing exercise showed no remarkable change in functional adaptability. A trend toward a decrease in exercise tolerances was evident as judged by the time necessary to reach a heart rate of 170 beats/min. The results of the exercise tolerance test are shown in Table 6-VI. Master's two-step ECG responses taken before and after the experiment showed no abnormalities.

Pulmonary function studies were performed initially, and periodically during the course of the experiment. The effects of the condition of the experiment on supine vital capacity, timed vital capacity, and maximum breathing capacity are shown in Table 6-VII. The table indicates a definite improvement in some parameters, especially in maximum breathing capacity. However, it is believed that parameters of this nature are only reproducible to ± 20% at best and that any additional trends can be contributed to learning, intensive coaching, and individual motivation. In subject BS, the great improvement seen in maximum breathing capacity between T-1 and T-20, for example, was probably the result of recovery from an upper-respiratory infection, which had produced a typical clinical picture of rhinorrhea, conjunctivitis, and a slight cough.*

6.2.2 Diagnostic Tests

There were no significant changes or trends in hemoglobin, white cell count, electrolytes, serum calcium, and phosphorus or protein-bound iodine (PBI) determinations as the result of the conditions of the experiment. Table 6-VIII summarizes some of the results of the blood chemistries done

*None of the other subjects exhibited signs or symptoms of U. R. I.

Table 6-VII
RESPIRATORY RESPONSES

GROUP	SUBJECT	DATE OF DETERMINATION														
		T-1			T-20			T-27			T-35			T-41		
		VC*	TVC**	MBC***	VC	TVC	MBC	VC	TVC	MBC	VC	TVC	MBC	VC	TVC	MBC
+1 g_z	BW	5.42	80.0	150	5.50	90.0	209	5.75	90.5	189	5.79	90.9	234	5.92	89.6	230
	NK	6.02	86.0	215	6.31	87.2	272	6.39	84.0	266	6.52	84.4	277	6.60	84.3	281
+4 g_z	LB	3.11	79.0	148	3.09	81.8	145	3.39	82.0	134	3.91	80.6	146.7	3.82	82.8	154
	GK	5.85	73.0	178	6.30	72.0	228	6.33	74.4	198	6.51	75.1	223	6.42	76.2	237
	BS	4.32	76.0	108	4.63	79.6	170	4.49	84.1	148	4.40	82.9	169	4.44	84.3	164

*Liters
**% VC within 1 sec.
***Liters/min.

Table 6-VIII
BLOOD CHEMISTRIES

GROUP	SUBJECT	DATE OF DETERMINATION																									
		T-1						T-21						T-31						T-36						BR-1					
		Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P
+1 g_z	BW	137	4.5	105	23	5.2	3.6	138	4.2	100	22	4.9	4.2	143	4.5	101	29	5.1	4.2	146	4.3	102	31	5.3	4.4	138	4.2	103	33	4.9	4.0
	NK	134	4.5	107	21	5.0	2.4	142	4.3	100	21	5.1	3.8	143	4.4	104	27	4.9	3.6	138	4.4	102	17	5.4	4.3	136	4.4	105	26	4.2	4.0
+4 g_z	LB	137	4.5	101	25	5.0	3.8	142	3.7	100	23	5.0	3.9	141	4.0	102	29	5.2	4.3	146	4.2	99	30	5.4	4.6	138	4.1	99	28	5.2	3.8
	GK	141	4.5	101	22	5.0	3.1	140	3.7	99	23	4.7	4.2	144	4.5	101	29	5.1	4.3	139	4.4	102	27	5.4	4.7	141	4.4	97	29	5.0	4.0
	BS	136	4.5	108	22	4.9	3.5	138	4.0	101	21	4.7	4.6	138	4.3	104	29	4.8	4.3	144	4.3	103	29	5.3	5.0	138	4.2	102	28	4.8	4.0

*Entries are meq/L except P = mg%

at regular intervals during the 41 days of experimentation. Urinalysis showed no remarkable changes attributable to the process of deconditioning or reconditioning on the centrifuge. Microscopic examination of the urine showed only an occasional white cell. All urine samples were free of sugar, acetone, and protein. Urine pH and specific gravity showed variations within a normal range. Analysis of the urine for creatinine, calcium, and phosphorus (inorganic) showed quantitative variations appropriate to the age and sex of the subjects. The remarkable constancy of these biomedical constituents of the urine can be seen in Table 6-IX.

A significant decrease in circumference of the limbs was not found. Variations of 1 to 2 cm were recorded; however, these were well within the error of measurement. Apparently, no demonstrable muscle atrophy took place.

Declines in plasma volumes in four of the five subjects at the end of 20 days of recumbency ranged from 242 to 740 ml or 11 to 22%. Decreases in total blood volume for this same period ranged from 240 to 980 ml or 7 to 18%. One subject (GK) showed no change in plasma or blood volume; however, the accuracy of the T-1824 method is reported to be 5%. Table 6-X gives hematocrits, plasma, and blood volumes at six consecutive points in the experiment. Neither periodic centrifugation nor exercise influenced blood volume in a consistent way. On the 41st day of the experiment, a plasma deficit, which ranged from 130 to 600 ml or 4.5 to 18%, was still apparent. Blood volumes ranged from 340 to 1160 ml for a percentage deficit of 10 to 19%, respectively. There was a small decrease in hematocrits from the initial values.

Table 6-IX
URINE CHEMISTRIES

GROUP	SUBJECT	DATE OF DETERMINATION														
		T-1			T-21			T-31			T-36			BR-1		
		Ca^{++}*	P**	Creatinine**	Ca^{++}	P	Creatinine	Ca^{++}	P	Creatinine	Ca^{++}	P	Creatinine	Ca^{++}	P	Creatinine
+1 g_z	BW	16	0.99	1.642	26	1.3	1.280	22	0.96	1.520	18	1.1	1.445	21	0.94	1.920
	NK	17	1.4	2.490	23	1.5	2.090	22	1.5	2.610	19	1.5	2.470	16	0.73	2.480
+4 g_z	LB	15	1.7	2.344	12	1.1	1.465	13	0.93	1.650	11	1.2	1.615	13	0.91	1.530
	GK	16	1.6	2.220	19	1.3	1.660	18	0.95	1.640	20	1.4	2.100	16	0.95	1.680
	BS	8.7	1.4	2.400	9.3	0.87	1.200	11	0.78	1.428	13	1.2	2.030	10	1.0	1.545

*Meq/24 hours
**g/24 hours

Table 6-X

HEMATOCRITS, PLASMA, AND BLOOD VOLUMES

GROUP	SUBJECT	DATE OF DETERMINATION					
		T-1	T-21	T-31	T-36	BR-1	BR-10
+1 g_z	BW	40*	43	44	41	40	38
		3,350†	2,610	2,475	2,770	2,940	3,080
		5,400	4,420	4,270	4,560	4,770	4,850
	NK	47	50	48	46	46	43
		3,320	2,990	2,930	3,590	2,720	3,530
		6,030	5,750	5,422	6,400	4,870	6,000
+4 g_z	LB	43	46	45	45	44	40
		2,090	1,848	1,810	1,610	1,850	2,090
		3,540	3,300	3,175	2,836	3,200	3,390
	GK	48	50	49	48	45	44
		2,870	2,940	2,880	2,520	2,740	3,330
		5,320	5,650	5,430	4,660	4,830	5,760
	BS	46	48	48	48	46	42
		2,780	2,430	2,550	2,520	2,450	2,830
		4,960	4,500	4,720	4,660	4,400	4,740

*Hematocrits in percent
†Volumes in ml

The body-weight changes during the various periods of the study are given in Table 6-XI. Changes in weight were progressive and ranged from a gain of 0.4 kg to a loss of 5.8 kg. Relative alterations in body composition were also recorded. Lean body mass showed an insignificant increase in two subjects and a decrease in three others. These changes ranged from a gain of 1.9 kg in lean mass to a loss of 6.7 kg.

Table 6-XI

BODY WEIGHT AND COMPOSITION

GROUP	SUBJECT	DATE OF DETERMINATION												
		B-1			T-16	T-20	T-34	T-41	BR-2			Difference		
		Total	Lean	Fat	Total	Total	Total	Total	Total	Lean	Fat	Total	Lean	Fat
+1 g_z	BW	64.0	52.1	11.9	62.8	62.6	62.7	62.0	61.6	49.8	11.8	-2.4	-2 3	-0.1
	NK	78.4	64.4	14.0	76.3	76.7	75.9	75.1	75.0	64.8	10.2	-3.4	+0.4	-3.8
+4 g_z	LB	60.7	46.7	14.0	61.6	61.1	60.6	60.7	61.1	48.6	12.5	+0.4	+1.9	-1.5
	GK	91.8	68.2	23.6	87.8	87.3	86.3	86.1	86.0	61.5	24.5	-5.8	-6.7	+0.9
	BS	73.7	60.7	13.0	73.4	72.7	73.2	73.5	72.3	54.8	17.5	-1.4	-5.9	+4.5

Entries are in kg

6.2.3 Monitoring Tests

Blood-pressure readings, made three times daily, revealed no marked change. Pulse pressure remained relatively constant throughout the 41-day period. Systolic and diastolic pressures taken at 0200 hours were slightly lower than those taken at 1030 and 1700 hours. Heart rate showed a similar diurnal variation. Heart rates varied between 50 and 70 beats/min with some individual variation. Respiratory rates remained relatively constant at 14 to 18 breaths/min. Oral temperatures ranged from 97° to 98.6°F.

During tilt-table tests, results indicated a definite deterioration of the mechanisms essential for adequate circulation brought about by the 20 days of recumbency. Syncope, or a tendency toward syncope, developed during the tilt procedures. Venous engorgement and increased extravascular fluid, and capillary fragility or permeability were noted during the first 5 days of centrifuge rides as evidenced by mild edema and petechiae. The subjects also noted symptoms such as tingling of their feet or pressure during the initial 5 days of centrifugation. These symptoms were noted especially in the +4 g_z group.

During tilt-table tests, heart rate and blood pressure were sampled at 1-min intervals. After periodic centrifugation, it was found that there was less lability in heart rate and blood pressure in the +4 g_z group when compared to the +1 g_z group. After 5 days of centrifugation, there was no further evidence of new petechiae or edema.

Medical summaries prepared by the duty nurse and augmented by the experimenters showed that the subjects accepted the inconveniences of the experimental procedures with great equanimity. Interpersonal relations existing before the experiment began were maintained, and apparently no new ones were established. Minor social problems that arose were handled by the subjects (that is, by use of the telephone), and only infrequently were the experimenters asked to intervene. A serious external social problem did exist for one subject throughout the course of the experiment. Morale was high, however, and as one subject put it, "They also serve who only lie and wait."

Appetites were good,and the subjects adjusted quickly to using the bed-pan and bed bath and to maintaining the long axis of the cardiovascular system horizontal at all times.

During the reconditioning period, the subjects expressed opinions about the efficacy of the centrifuge regimen. They felt it had a salubrious effect although it was a little monotonous.

In recovery, the subjects reported some stiffness and soreness of their joints, particularly the feet and ankles, during the first few days. After nearly 1-1/2 months of viewing the world from the horizontal, reactions reported on the first hours of recovery ranged from "pin pricks on the soles of my feet" to a feeling that "the floor was tilted backwards." At the conclusion of the recovery period on the 51st day, one subject went on a ski holiday and reported that his activities on the slope were no worse than usual.

6.3 SUMMARY

This pilot study was made on the influence of periodic centrifugation on physiological disturbances associated with 41 days of recumbency. The subjects were five healthy, young men. The investigation was carried out in a biodynamic ward during 20 days of bed rest; 16 days of bed rest with periodic rides on a short-radius (4.5 ft) centrifuge; 5 days of bed rest, centrifugation, and physical exercise; and a 10-day recovery period. From the 21st to 41st day, the subjects rode the centrifuge four times each day (2 hours between successive rides and 6 hours between the start of the first and last ride of the day); the duration of each ride was 7.5 min. The level of acceleration was +1 g_z for one group and +4 g_z for the other. Because the heart-to-foot acceleration gradient was 219%, the level of acceleration was referenced to the subjects' feet.

Functional tests conducted before and after the 41 days of recumbency showed no appreciable change in exercise tolerance (treadmill and Master's two-step ECG) or for tolerance to acceleration in the $+g_z$ vector. Observational data support the results of these tests (for example, one subject went on a ski holiday at the end of the recovery period).

Functional and diagnostic tests conducted at regular intervals during 41 days of recumbency revealed the following:

1. Reports by the subjects and observations made by the experimenters indicate that a steep heart-to-foot acceleration gradient does not preclude movement of the head, arms, and legs; and that motion sickness is not a problem for the well-trained individual when exposed to high rates of rotation and modest head or limb movements.

2. The deterioration produced by recumbency in the ability of the subjects to tolerate 90° head-up tilt for 20 min was largely prevented by periodic centrifugation. The subjects receiving a +4 g_z four times each day showed less lability in blood pressure and heart rate during the tilt-table tests than did the subjects exposed to +1 g_z. The absence of any new petechiae and edema after the first days of riding the centrifuge is evidence for no apparent decrease in capillary-wall fragility or permeability.

3. Twenty days of recumbency brought about a deterioration in the mechanisms essential for adequate circulation in the erect position as indicated (1) by syncope or a tendency to faint during tilt-table tests; (2) by venous engorgement, increased extravascular fluid and capillary fragility seen during the first days of riding the centrifuge; and (3) by declines in plasma and blood volumes.

4. Changes in body weight during the experiment were progressive and ranged from a gain of 0.4 kg to a loss of 5.8 kg, while lean body mass decreased in three subjects.

5. There were no significant changes or trends, resulting from the conditions of the experiment, in electrocardiograms, resting blood pressure, or heart rate; blood counts, electrolytes, serum calcium, phosphorus, or protein-bound iodine; microscopic or qualitative analysis of the urine for sugar, acetone, or protein; urinary specific gravity, pH, or in urinary calcium, phosphorus and creatinine; vital capacity, resting respiration rate, timed vital capacity, or maximum breathing capacity; or limb girth.

6. Recovery or return toward control levels of physiological function took place within the 10-day recovery period.

6.4 REFERENCE

6-1 Allen, T. H. Measurement of Human Body Fat: A Quantitative Method Suited for Use by Aviation Medical Officers, SAM-TDR-63-45, USAF School of Aerospace Medicine, Brooks AFB, Texas, 1963.

Section VII

INFLUENCE OF PERIODIC CENTRIFUGATION AND EXERCISE ON PHYSIOLOGICAL FUNCTION DURING RECUMBENCY

The purpose of this pilot study was to extend the results of the previous study by means of the following changes:

1. Giving all the subjects an exercise regimen of approximately 700 kcal/day.
2. Increasing the integrated g-time exposure from 0.5 and 2 g-hours to 3 g-hours.
3. Distributing the four rides on the centrifuge over a 24-hour period as contrasted with the 8-hour schedule of the first study.

In addition to these changes, the number of subjects used in the experiment was increased from 5 to 12 and divided evenly into one control group and two experimental groups. The control group was transported to and from the centrifuge, but was not rotated. The first experimental group, the maintenance group, began riding the centrifuge on the first day of bed rest and rode every day for 13 days. The second group, the therapeutic group, started riding the centrifuge after 17 days of bed rest and rode every day for 6 days.

7.1 METHOD

A detailed discussion of the experimental method is presented below.

7.1.1 Subjects

Twelve normal, healthy men were studied while on a constant diet during the experiment. All were paid volunteers who were free to withdraw from the experiment at any time. The subjects were briefed prior to, during, and at the conclusion of the experiment as to the protocol, the probable risk, and the steps taken to ensure their health and welfare. All subjects agreed in writing to the use of radioactive drugs. Admitting history, Master's two-step ECG, and urinalysis were normal. Physical examination and blood

analysis (differential white count) showed that several of the subjects had mild upper respiratory infections (probably viral) at the beginning of the experiment.† The maintenance group consisted of those subjects who had participated in the previously described bed-rest study. The control and therapy group had no previous experience with bed-rest studies and only limited experience in riding the centrifuge. Physical characteristics of the subjects are shown in Table 7-1. All of the subjects completing this study signed up for follow-on experiments.

Table 7-1

PHYSICAL CHARACTERISTICS OF SUBJECTS

GROUP	SUBJECT	AGE	HEIGHT (cm)	WEIGHT (kg)	PLASMA VOL LEAN MASS (ml/kg)
Control	JA	21	178.4	78.27	58.3
	CB	27	184.8	78.98	57.0
	HK	23	179.1	72.45	54.1
	RM	24	189.2	84.05	56.3
Maintenance	NK*	28	180.0	78.63	48.4
	LB**	25	169.9	62.54	41.9
	RE	25	167.0	67.73	47.3
	GK	22	175.9	88.98	52.1
	BS	22	178.1	71.09	50.4
Therapy	GM	30	179.1	74.52	62.4
	LS	24	174.0	73.68	43.4
	FS	22	179.1	92.53	55.7

* Voluntarily withdrew on T-4
**Withdrawn for medical reasons on T-11

† Symptoms and signs of mild U.R.I. were exhibited by 8 of the 12 subjects. Subjects involved were: JA, CB, HK, LB, GK, BS, GM, and LS. They had a slight "sore throat," mild inflammation of the pharnyx, and mild rhinorrhea. In addition to the above, subject JA had mild conjunctivitis; subject HK had an occasional loose cough, but his chest was clear. These two men and subject BS received no medication. The remaining subjects were given one Ornade spansule, one 25 gtts dose of Gly-oxide, and one dose of A.S.A. gr X. All medication was administered on T-3. These symptoms and signs were first recorded on T-2, and all subjects were free of U.R.I. by T-6. The duration of the U.R.I. was, on the average, 3 days. These U.R.I. were not accompanied by fever, malaise, or significant exudate. The subjects were judged to be medically qualified to continue their participation in the experiment. Subjects NK, RM, RE, and FS showed no evidence of U.R.I.

During this experiment, there were five incidents that are of interest to the specialist in aerospace medicine. They are reported in detail in the appendix of this report. Subject NK voluntarily withdrew from the experiment on the afternoon of the fourth day (T-4) of bed rest. He complained of vertigo and gave personal obligations as the reasons for withdrawing from the experiment. The particulars of his withdrawal are discussed in the appendix. On the evening of the third day (T-3), subject RE was transferred from the therapy to the maintenance group as a replacement. Subject LB was removed from the experiment on the 11th day of bed rest (T-11) after experiencing a disturbance in cardiac rhythm and syncope during a maintenance ride on the centrifuge. All other subjects completed the experiment, although subjects BS and GK of the maintenance group, and subject HK of the control group showed cardiac abnormalities during the second of a series of three bioassay runs. The subjects were placed on a calculated 2,791 kcal diet, with an average daily calcium intake of 0.9 gm. The basic meal plan is shown in Table 7-II.

7.1.2 Baseline and Intercurrent Measures

Table 7-III lists the functional, diagnostic, and monitoring tests performed during the program. The table gives the dates of each administration of the tests. Tests administered once, for example, VDRL, or tests indirectly related to the program, such as nose and throat cultures, are not shown in the table.

The tilt-table test was used to measure the functional reserve of the cardiovascular system. The subject, seated in a saddle, was tilted to 64°, feet downward, for 20 min (unless syncope intervened). Figure 7-1 shows a subject on the tilt table. Heart-rate and blood-pressure readings were taken every minute before, during, and after the tilt test. All tilt-table tests were conducted by the same physician. Electrocardiograms were taken continuously during the tilt test. A Flack test--maintaining airway pressure of

TABLE 7-II

BASIC MEAL PLAN

Breakfast--0700 Hours

1 serving fruit
1 serving cereal with sugar
4 oz nonfat milk
1 egg
1 slice toast with margarine
coffee
sugar

Snack--1000 Hours

1 serving graham crackers
1 serving fruit

Afternoon Meal--1300 Hours

1 serving fish, poultry, or meat
1 serving starchy vegetable
margarine
1 serving cooked vegetable
1 serving raw vegetable
salad dressing
1 serving fruit and/or pastry
coffee, black
sugar

Snack--1600 Hours

1 serving ritz crackers
1 serving peanut butter

Evening Meal--1900 Hours

1 serving fish, poultry, or meat
1 serving starchy vegetable
1 serving cooked vegetable
1 serving raw vegetable
salad dressing
8 oz whole milk
1 serving fruit and/or pastry
coffee
sugar

Bedtime

1 serving graham crackers

Table 7-III

BASELINE AND INTERCURRENT MEASURES

TESTS	DATES ADMINISTERED
FUNCTIONAL	
Orthostatic tolerance & Flack test	B-2,* B-3, T-14, T-17, BR-1
Acceleration tolerance	B-3, T-15, T-16, BR-2
Posture tests	B-2, T-17, BR-3
DIAGNOSTIC	
CBC	B-3, T-14, BR-1
Serum electrolytes	B-3, T-14, BR-1
Serum calcium	B-3, T-14, BR-1
Serum phosphorus	B-3, T-14, BR-1
Serum electrophoresis	B-3, T-14, BR-1
Plasma (I^{131}) and blood volume	B-3, T-14, T-17, BR-1
Extracellular fluid (S^{35})	B-3, T-14, T-17, BR-1
Routine urinalysis	B-3, T-14, BR-2
Calcium	B-3, T-14, BR-2
Phosphorus	B-3, T-14, BR-2
17 ketosteroids	B-3, T-14, BR-2
17 ketogenic steroids	B-3, T-14, BR-2
Body weight	B-1, T-8, T-13, T-20, BR-2
MONITORING	
Blood pressure	Daily
Heart and respiration rates	
Temperature	
Fluid intake/output	
Medical summary	

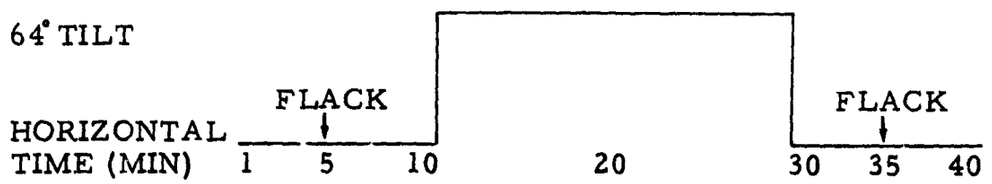
*B = Baseline (B-1 = 1/9/65)

T = Bed Rest (T-1 = 1/12/65)

BR = Baseline-Recovery (BR-1 = 2/4/65)

Figure 7-1. Tilt Table at 64° With Saddle Support

40 mm Hg for 30 sec by blowing through a resistance tube -- was administered 5 min prior to and following head-up tilt. The tilt profile was as follows:



The subject was allowed to lie quietly for 10 min prior to and following the head-up tilt. The entire procedure required 40 min.

To determine tolerance to positive acceleration, bioassay runs were conducted on the centrifuge. A modification of the conventional bioassay method was used (Reference 2-6). The intensity of a centrally fixated red light was adjusted so that it was 0.2 logarithmic units above foveal threshold.

The subject responded to this light in the conventional manner by turning it off when it appeared. Blackout was reached when the subject could no longer see the light. At this point, a second but brighter light was turned on. By turning off the second light, the subject signaled, in effect, that the expected changes in retinal blood flow had taken place. The rate of onset for bioassay runs was 0.2 g/sec until blackout, followed by a slow decay of angular velocity. The radius from the center of rotation to heart level was 16 in.; acceleration gradient was 219%. Because of the gradient, +4 g_z at the heart was set as the upper limit of exposure.

The routine double Master's test with a 12-lead electrocardiogram was taken in the conventional manner. The results of this test were analyzed by a consulting cardiologist.

The Graybiel-Fregly posture test uses rails that are a modification of those originally used to screen American astronauts. In the present experiment, the short form of this postural equilibrium test was used. There were five trials on each of three tasks:

1. Walking heel-to-toe on a 0.75-in. rail for five steps or until balance could not be maintained, with the arms folded against the chest.
2. Standing heel-to-toe, with eyes open and arms folded, on the 0.75-in. rail until the subject fell off the rail.
3. Standing on a 2.25-in. rail, with eyes closed and arms folded, until the subject fell off the rail.

Scoring was based on the best three out of five trials; maximum score for walking was 15 steps and for standing, 180 sec.

Urine and blood samples were analyzed in a conventional quantitative and qualitative manner.* Total body water, extracellular fluid, and plasma and blood volumes were determined using radioisotopes and the protocol developed by Dietlein and his colleagues (Reference 7-1). Determination of total body water ($H_2{}^3O$) was not possible because counting rates were so low that counting time was prohibitive.

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*Diagnostic tests were performed by Bio-Science Laboratories, Los Angeles, California

Monitoring tests shown in Table 7-III followed hospital ward routine. In addition, each subject was asked to prepare written comments on his feelings and reactions to the experiment.

7.1.3 Experimental Plan

The bed-rest analog of null gravity lacks the element of physical activity expected in orbital laboratories. Estimated energy expenditure of a young, average-sized man in orbit would amount to 2,500 kcal/day (Reference 7-2). Planned activities, for example, extravehicular operations, would require an additional 300 kcal. In an effort to increase the fidelity of the analog, 700 kcal were added to a basic 2,100 kcal diet, and a bicycle ergometer was used to define the level of activity. A standard work load on the ergometer was 200 watts for 68 min/day. This workload was arrived at by measuring oxygen consumption while the subject pedaled the ergometer. Figures 7-2 and 7-3 show the ergometer and the apparatus used for the collection of expired gases before, during, and after a period of exercise.

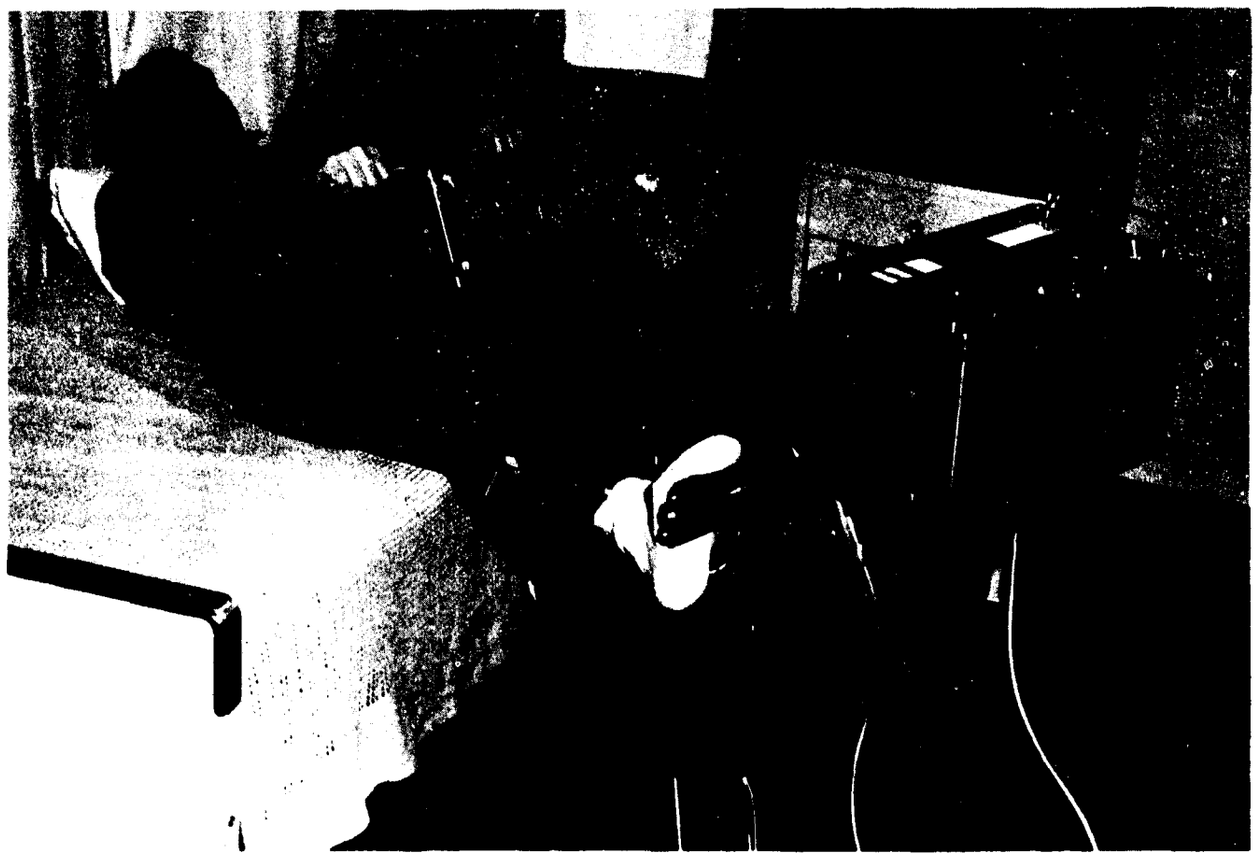


Figure 7-2. Bicycle Ergometer

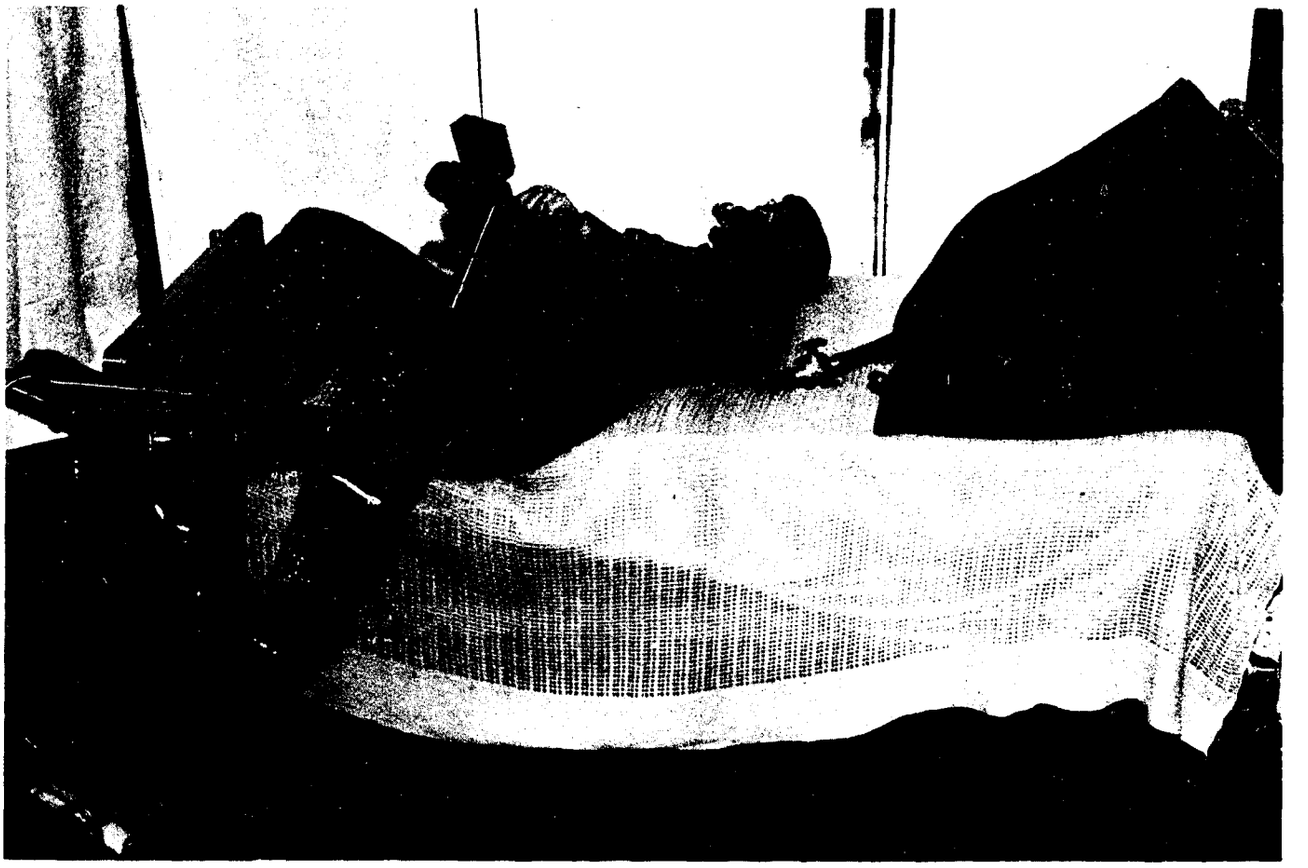


Figure 7-3. Measurement of Oxygen Consumption While Pedaling the Ergometer

Gas samples were analyzed for oxygen, carbon dioxide, and nitrogen using gas chromatography. These analyses showed that pedaling the ergometer at 200 watts for 17 min required from 150 to 175 kcal.

Initially, exercise activity was performed every 6 hours and followed the centrifuge time schedule. After four days, general fatigue prevented adherence to this schedule,and it was modified at the subjects' request so that all the exercise was done during one period of the day. The new schedule massed the exercise into four 17-min periods,with 10-min breaks between these periods. This modified schedule and work load were used by the subjects in the control, maintenance, and therapy groups. Prior to the start of the study, all subjects exercised twice daily for 1 week on the ergometer and threadmill. This training brought the work load within the physical capabilities of the subjects, and training also improved the ability of the subjects to use the ergometer while in the supine position.

The parameter and protocol followed in this study are shown in Table 7-IV. On the first day of the experiment, the subjects were split into control, maintenance, and therapy groups. The difference between the control and the two experimental groups was in the g-time parameter. All groups were transferred to and from the centrifuge; however, the experimental groups rode the centrifuge and were exposed to +4 g_z at the feet. The maintenance group started riding the centrifuge on the first day of bed rest (T-1) and rode according to the specified schedule for 13 days. The therapy group started riding the centrifuge after 17 days of bed rest (T-18) and rode on schedule for 6 days (T-23). The heart-to-foot acceleration gradient was 219% for both groups.

The duration of a ride on the centrifuge was 11.2 min, the frequency of exposure was 4 times/day, and both were arrived at on the basis of parameterization of time and hydrostatic pressure. By increasing the duration of exposure from 7.5 min used in the first study to 11.2 min, and using +4 g_z as the level of acceleration, the g-time integral becomes 3 g-hours. The maximum integrated g-time exposure in the first study was 2 g-hours.

Subjects followed a ride schedule that called for 6 hours between successive rides. The first ride occurred at 0630, the second at 1230, the third at 1830, and the fourth at 0030 hours. For the purpose of economy, the subjects were transported two at a time from their beds to the centrifuge, and from the centrifuge back to bed. The arrangement of the dual sling is shown in Figure 7-4. The position of the subjects on the centrifuge was identical to that of the first study.

7.2 RESULTS

A detailed discussion of the experimental results is presented below.

7.2.1 Functional Tests

The results of the tilt-table tests of orthostatic tolerance are summarized numerically in Table 7-V and are presented graphically in Figure 7-5 for each subject. During the baseline period prior to the beginning of the experiment, all subjects were tested on the tilt table. All subjects

Table 7-IV

EXPERIMENTAL PLAN

PARAMETER	CONTROL GROUP	MAINTENANCE GROUP	THERAPY GROUP
g-Time	≅ 0	3.0 g-hr	3.0 g-hr
Effective* hydrostatic pressure	≅ 0	177 mm Hg	177 mm Hg
No. of subjects	4	3	3
Heart-to-foot g gradient	0%	219%	219%
Dose rate	N.A.	Four 11.2-min rides/ 24 hr	Four 11.2-min rides/ 24 hr
Exercise	Δ 700 kcal	Δ 700 kcal	Δ 700 kcal
Protocol	3 days baseline (B-1 to B-3)	3 days baseline (B-1 to B-3)	3 days baseline (B-1 to B-3)
	23 days bed rest + exercise (T-1 to T-23)	13 days bed rest + exercise + g (T-1 to T-13)	17 days bed rest + exercise (T-1 to T-17)
			6 days bed rest + exercise + g (T-18 to T-23)
	4 days baseline and recovery (BR-1 to BR-4)	3 days baseline and recovery (BR-1 to BR-3)	4 days baseline and recovery (BR-1 to BR-4)

*At the feet

tolerated the test well and reported feeling alert during the entire procedure. Minimal pallor was the only symptom noted. The heart rates of all subjects were regular and remained below 100 beats/min. Blood and pulse pressures were all within a normal range. The Flack test administered before and after tilt resulted in elevated heart rates and blood pressures. The dynamics of the blood pressure changes during the Flack test made this a difficult measure to obtain accurately. ECG records were used to compute the maximum heart rates shown on each graph.

After 13 days (T-14) of bed rest, the control and maintenance groups were again tilted. All subjects in the maintenance group showed an excellent response to tilt. They had minimal pallor, and normal blood and pulse pressures. Their heart rates were well below 100 beats/min, and they were quite alert throughout the procedure. Integrated heart rates (obtained by planimetry) were 5 to 12% higher than baseline rates. The control group

Figure 7-4. Dual Sling for Transporting Subjects from Bed to Centrifuge and Return

GROUP	SUBJECT	B-2, B-3			
		Time*	$\int_1^{20}$ Heart Rate dt **	$\int_1^{20}$ Pulse Pressure dt ***	M
Control	JA	20	1700	470	
	CB	20	1586	404	
	HK	20	1772	458	
	RM	20	1454	484	
Maintenance	RE	20	1424	1158	
	GK	20	1381	678	
	BS	20	1438	516	
Therapy	GM	20	1600	454	
	LS	20	1570	680	
	FS	20	1432	502	

* min
** beats
*** mm Hg
M. A. P. = Mean Arterial Pressure (mm Hg)

DURATION, H
A

DATE OF DETERMINATION							
	T-14 & T-17						
*** re dt	M.A.P.	Time	$\int_1^{20}$ Heart Rate dt	$\int_1^{20}$ Pulse Pressure dt	M.A.P.	Time	$\int_1^{20}$
	101.7	20	1564	364	90.4	6	
	105.8	20	1466	342	102.0	20	
	102.7	20	1720	554	94.6	6	
	99.4	13	1150	140	97.6	20	
	101.1	20	1492	872	94.9	–	
	102.7	20	1516	532	95.6	–	
	97.6	20	1614	390	94.0	–	
	106.6	15	1198	222	98.1	10	
	97.2	5	330	126	80.8	8	
	102.1	20	1722	354	102.3	20	

2

Table 7-V

HI
AR

DURATION, HEART RATE, PULSE PRESSURE, AND MEAN ARTERIAL PRESSURE DURING TILT

-17		BR-1			
0 $\int$ Pulse Pressure dt	M. A. P.	Time	$\int_1^{20}$ Heart Rate dt	$\int_1^{20}$ Pulse Pressure dt	M. A. P.
364	90.4	6	546	44	89.0
342	102.0	20	1884	202	97.4
554	94.6	6	536	132	82.0
140	97.6	20	1836	282	101.6
872	94.9	–	–	–	–
532	95.6	–	–	–	–
390	94.0	–	–	–	–
222	98.1	10	748	212	97.5
126	80.8	8	678	166	88.4
354	102.3	20	1650	478	104.7

3

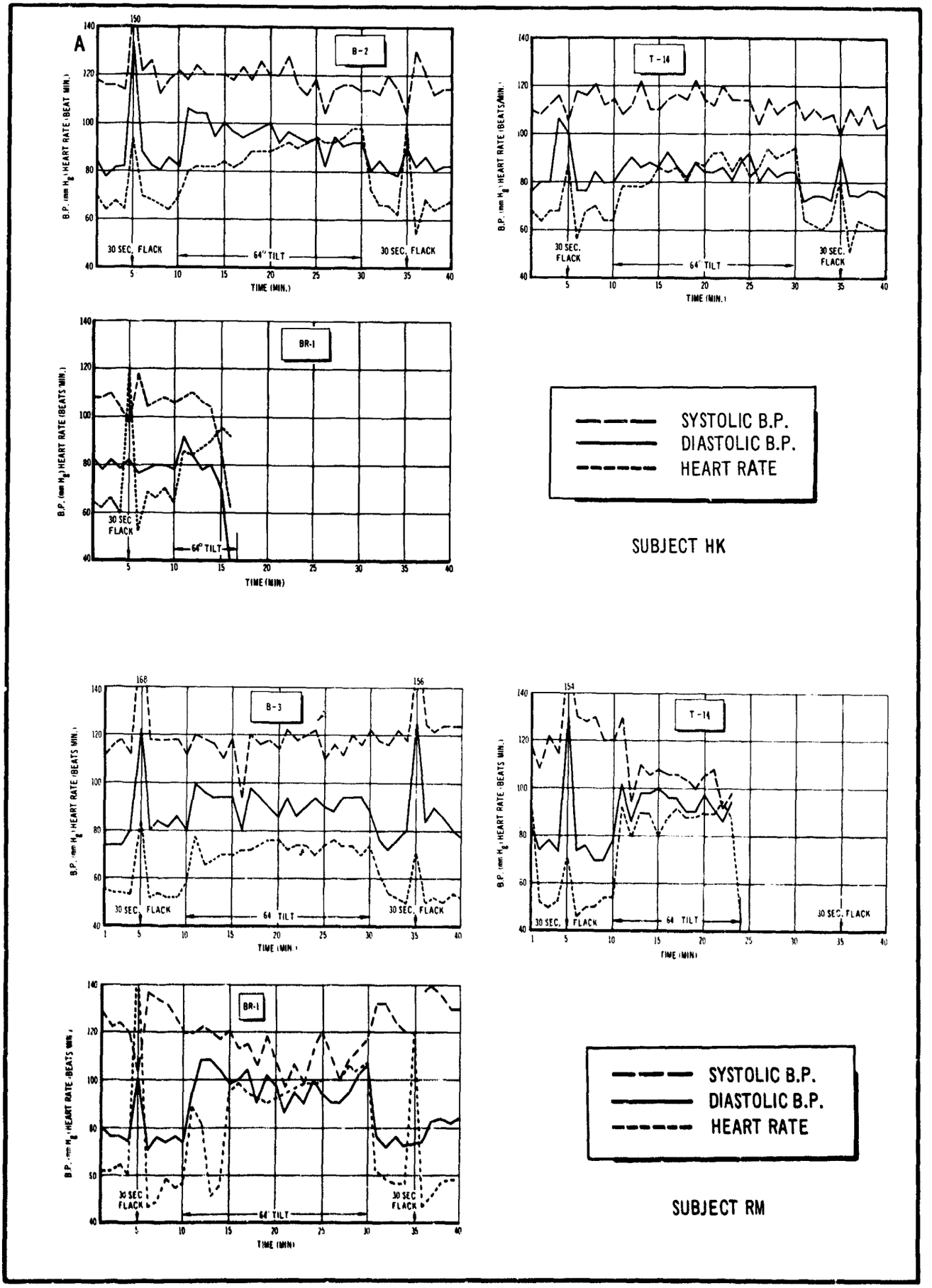
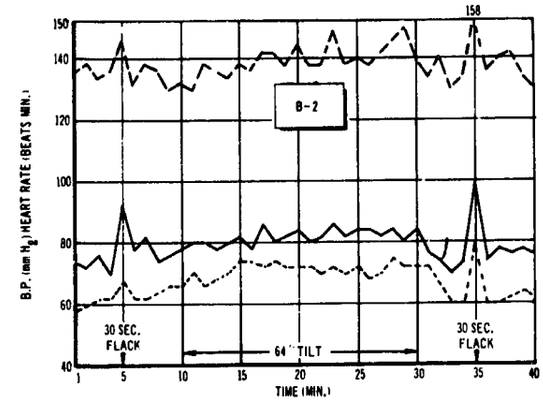
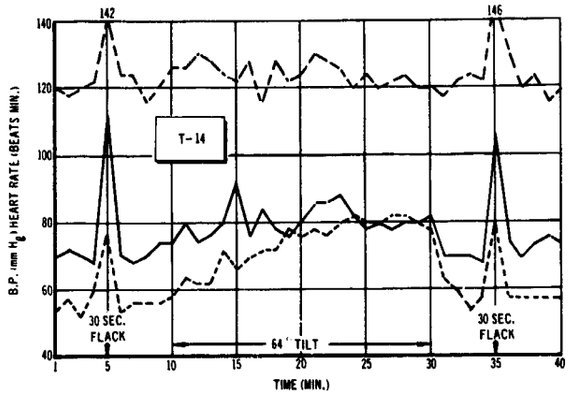


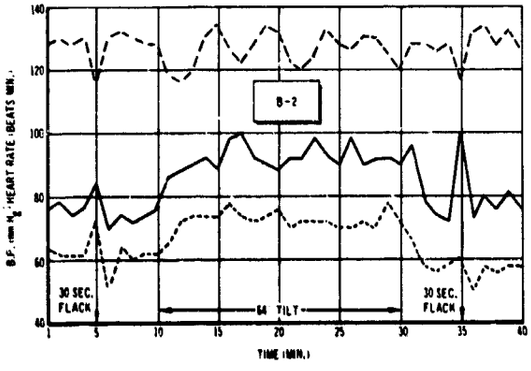
Figure7-5. (Continued)

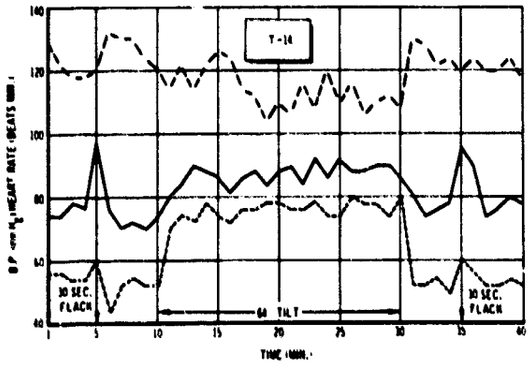




SYSTOLIC B.P.
DIASTOLIC B.P.
HEART RATE

SUBJECT RE

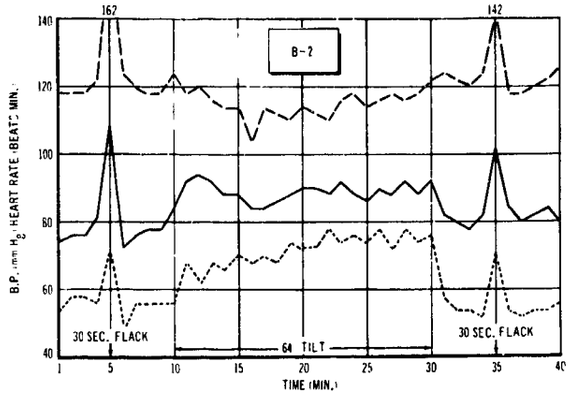


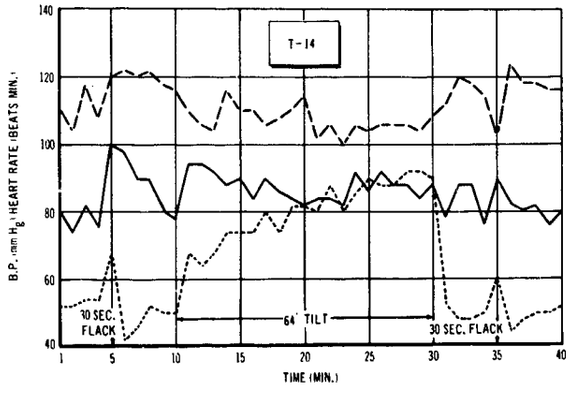


SYSTOLIC B.P.
DIASTOLIC B.P.
HEART RATE

SUBJECT GK

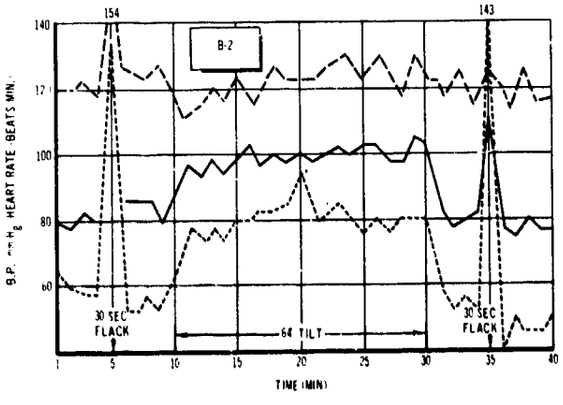
Figure 7-5. (Continued)

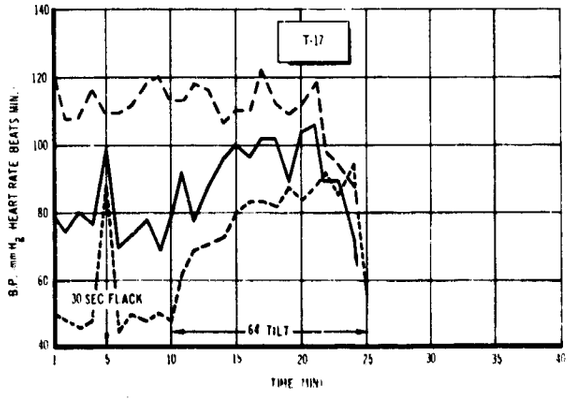


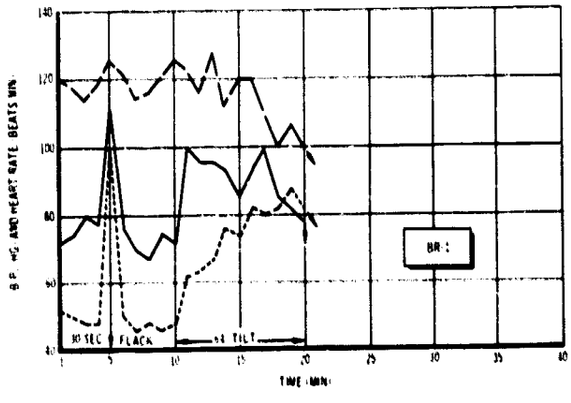


SYSTOLIC B.P.
DIASTOLIC B.P.
HEART RATE

SUBJECT BS







SYSTOLIC B.P.
DIASTOLIC B.P.
HEART RATE

SUBJECT GM

Figure 7-5. (Continued)

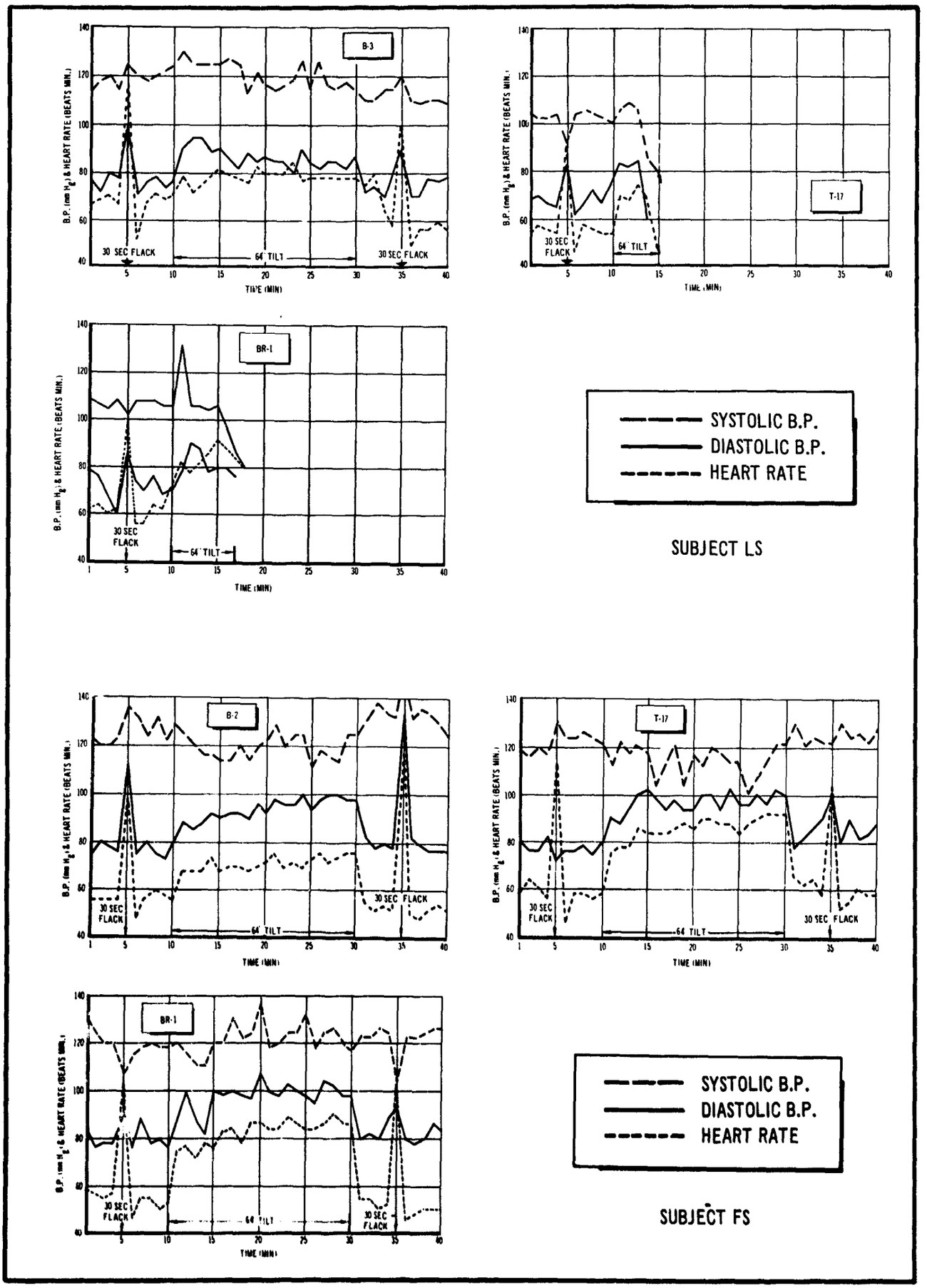


Figure 7-5. (Concluded)

did not consistently show cardiovascular deconditioning. Only one subject (RM) developed syncope and this occurred after 13 min of tilt. At the time of syncope his heart rate was 88 beats/min. One other control subject (JA) developed a drop in systolic pressure and mild pallor and showed definite signs of impending syncope just prior to scheduled termination of the test. Heart rates were below 100 beats/min in the control group. Except for subject RM, all subjects showed a 3 to 8% decrease in heart rates from baseline rates. There was some indication that the control group showed somewhat more pallor and less alertness during this tilt.

After 16 days (T-17) of bed rest, and just prior to starting periodic centrifugation, the therapy group was tilted. Two of the subjects developed syncope, one subject (LS) after 5 min of 64° head-up tilt and the other subject (GM), after 15 min. Heart rates were, as in the case of the control group, below 100 beats/min. The remaining subject (FS) showed a normal pulse pressure throughout the tilt and had a maximum rate of 90 beats/min. His integrated heart rate was about 20% higher than his rate during the baseline tilt test.

Since the control and therapy groups received the same treatment up to the 14th and 17th day, respectively, it is reasonable to compare their responses with those of the maintenance group. Use of periodic centrifugation and exercise during bed rest tended to prevent deterioration of the mechanisms essential for circulatory control on the tilt table. The effects of centrifugation were indicated by the lack of syncope in any of the tilt-table tests. In the control and therapy groups, three subjects developed syncope and one showed signs of impending syncope at the scheduled termination of the test. The remaining subjects presented a favorable clinical picture during tilt and, as a group, showed an integrated heart rate that was 9% higher than the rate during baseline tilts. The maintenance group showed the same modest increase in integrated heart rate. The effects of exercise were indicated by the heart rate response during tilt. Rates were always below 100 beats/min, and this figure is in sharp contrast with the previous study where rates in excess of 120 beats/min were common. This significant reduction in heart rate was probably produced by increasing or maintaining cardiac reserve and efficiency, and/or by increasing or maintaining

muscle tonus and, hence, more resistance to venous pooling in the lower extremities. No appreciable caloric exercise was included in the previous study, and the tilt tests were characterized by marked tachycardias and narrow pulse pressures.

Decrease in average pulse pressure between the first and second tilt-table tests was 3.5 mm Hg for both the control and the therapy groups, and in the same period the decrease was 9 mm Hg for the maintenance group. These average figures do not include the three subjects who developed syncope. Pulse pressures during the second tilt ranged from 17 to 27 mm Hg in the control and therapy groups, and from 20 to 43 mm Hg in the maintenance group; both ranges are above critical levels.

On T-14 the maintenance group terminated their period of bed rest and began their baseline recovery tests.

The control and therapy groups were again tilted on BR-1. For the control group, this tilt-table test was done after 23 days of bed rest and periodic exercise; for the therapy group, this test was done after 23 days of bed rest and periodic exercise, and after 6 days of periodic centrifugation. Two of the control group subjects (JA and HK) developed syncope after 6 min of tilt; their heart rates just prior to syncope were 95 and 100 beats/min, respectively. Subjects CB and RM showed a marked narrowing of pulse pressure and heart rates of 104 beats/min, and developed moderate pallor and cold extremities, but did not faint. Their average heart rates over the 20-min tilt were 94 and 91 beats/min; average pulse pressures were 10 and 14 mm Hg. In the preceeding tilt, subject RM developed syncope after 13 min. Subjects GM and LS of the therapy group developed syncope, while subject FS did not during this tilt test. Both of these subjects fainted during the previous tilt. Subject FS showed a pulse pressure increase of 32% over that recorded on the previous tilt and a 4% decrease in heart rate.

Comparison of the control and therapy groups after 23 days of experimentation shows that increasing the integrated g-time by lengthening the duration of exposure to a constant level of acceleration and the 24-hour ride schedule was not so effective as the earlier protocol in preventing

orthostatic intolerance. The effects of these two factors were indicated by syncopal episodes in two of the three subjects in the therapy group. The fact that one subject was showing a uniformly improved reaction to tilt suggests that continuation of the experiment may have produced beneficial effects for the other two subjects. The effects of exercise were indicated by the frequencey of fainting in the control group. In the previous study, 21 days of bed rest and no exercise produced significant cardiovascular deconditioning (that is, four of the five subjects developed syncope during 90° head-up, 20-min tilt). In this experiment, two of the four subjects who had been exposed to 23 days of bed rest and exercise developed syncope.

The relative effectiveness of centrifugation and exercise can be viewed in terms of the time required to modify the effects of bed rest on cardiovascular and musculoskeletal functions. The current set of data indicate that 45 min of maintenance centrifugation and 68 min of exercise performed nonconcurrently, favorably modify the effects of recumbency on circulatory control. A direction future research might profitably take is the optimization of the exposure protocol, and should include the study of the physiological consequences of exercising while riding a short-radius centrifuge. This combination may result in a significant reduction in the amount of time devoted to the maintenance of cardiovascular and musculoskeletal functions.

The cardiovascular changes produced by the Flack test were not intimately related to the conditions of the experiment. The rate of change of heart rate, and the maximum and minimum rates, could not be used to predict a subject's response to the tilt-table tests or to other tests conducted during the period of experimentation.

Tolerance to positive acceleration ($+g_z$) was measured before, during, and after the 23-day experimental period. Tolerance was measured with a low-intensity light and a gradual onset of acceleration to blackout or to a maximum of +4 g_z. The level of acceleration was referenced to the heart. Tolerance was measured on the short-radius centrifuge with a heart-to-foot gradient of 219%. A summary of the results is shown in Table 7-VI. A trend in the direction of reduced tolerance to positive acceleration is seen for

Table 7-VI

ACCELERATION TOLERANCE

GROUP	SUBJECT	DATE OF DETERMINATION		
		B-3	T-15 & T-16	BR-2
Control	JA	4.0*	3.2	3.5
	CB	4.0	3.5	3.4
	HK	3.2	3.2†	3.1†
	RM	3.3●	3.0	3.4
Maintenance	RE	4.0*	3.5	—
	GK	3.7	3.6†	—
	BS	3.8	3.5	—
Therapy	GM	3.5	3.2	3.5
	LS	3.5●	2.4	3.3●
	FS	3.8	4.0†	3.8

Entries are in $+g_z$ units at heart level.

* Terminated at maximum g.

● Terminated because of pain in legs.

† Became unconscious during decay, after central light loss.

the three groups; however, the magnitude of the loss is smaller for the two experimental groups. It is of interest to note that acceleration tolerance is in no apparent way related to performance on the tilt table. Knowledge about a subject's response to tilt is not helpful in predicting his tolerance to positive acceleration (Reference 7-3).

During the second series of bioassay runs (T-15), ECG changes were noted on subjects GK and BS of the maintenance group and on subject HK of the control group. All previous ECGs for these subjects were completely normal, including the ECGs taken during the initial bioassay runs before bed rest began. Subsequent bioassay runs (BR-2) on subject HK were completely normal. ECG irregularities were noted during the early morning runs after 12 hours of fasting. Subsequent bioassay runs were conducted after a meal so as to take advantage of the increased tolerance associated with gastric distension and the increased abdominal pressure this produces, and to avoid the possibility of hypoglycemia (References 7-4 and 7-5).

On T-15 at 0735, subject GK exhibited a completely normal ECG prior to his bioassay run. When reaching +3.6 g_z at the heart, his ECG was normal and exhibited the usual changes seen at this level of acceleration. These changes consisted of an increase in heart rate from a resting level of 70 to 150 beats/min and a decrease in amplitude of R waves with a concurrent increase in S waves and Q waves. After the subject had lost the central light, a planned decay in angular velocity commenced. At this time, he developed a rapidly increasing bradycardia, ranging from 150 to 75 to 36 beats/min within 10 to 12 sec after the start of deceleration. This was immediately followed by an asystole of 4.2 sec, at which time a nodal escape occurred, and this was followed by a second period of asystole of 11.2 sec which, in turn, was terminated by a second nodal escape. The second nodal escape was followed by a third and a fourth, at 29 and 30 sec after deceleration. Following these escapes, another period of asystole of 5.6 sec occurred. At this time, a probable nodal rhythm of 38 beats/min developed and gradually increased in rate until, at some point, a change to normal sinus rhythm was made so that 65 to 70 sec after deceleration the heart rate was 100 beats/min. From this point, normal sinus slowing occurred to approximately 55 to 60 beats/min and was followed by a gradually decreasing rate to as low as 42 beats/min, on occasion, with some sinus arrhythmia seen. The point at which nodal rhythm switched to sinus rhythm was obscured by muscle movement artifact. The subject did not respond to the light or buzzer; therefore, he was judged to be unconscious for approximately 1 min. He was completely asymptomatic following this run and indeed ate his breakfast immediately afterward. A standard 12-lead ECG was completely normal and remained normal throughout the next 3 days. A double Masters test on T-16 was normal.

Subject BS exhibited a completely normal ECG prior to a bioassay run on T-15 at 0830. The ECG at a peak of +3.5 g_z at heart level showed a heart-rate increase from 57 to 158 beats/min, with the usual changes in the amplitude of R and S waves. In addition, as is frequently seen at these heart rates, the T waves and P waves merged to form one large wave. Upon deceleration, P waves began to reappear at 10 sec following the onset of the decay and were separate from the T waves within 20 sec. The P-R interval was 0.12 to 0.14 sec until at 20 sec following deceleration, a complete atrioventricular

dissociation occurred with a concurrent heart rate change from 150 to 100 beats/min. The sinus node rate was 50 beats/min at this time. There was also at this time a 1.5 mm depression of ST segments which was not present before the run began. The QRS interval was 0.07 sec during the dissociation. There was occasional retrograde conduction of P waves from below the area of AV node delay, and occasionally a negative P wave was seen preceding the QRS complex. By 34 sec from onset of deceleration, the heart rate was down to 71 beats/min. The abnormality of conduction was seen for a 2-min period during and following deceleration. The subject was completely asymptomatic during this whole episode. A clinical ECG, employing the 12 standard leads, performed after the centrifuge ride, was normal. A double Masters test done on T-16 was completely normal.

Subject HK had a completely normal ECG prior to centrifugation on T-16. At +3.2 g_z, during a bioassy run, the ECG was also normal, and showed only the usual changes of decreased R waves and increased heart rate from 83 to 140 beats/min. Upon decay from peak acceleration of +3.2 g_z, the heart rate rapidly slowed from 140 to 100 beats/min in 6 sec, at which point bradycardia developed to a minimum of 28 beats/min for 2 beats. The heart rate then increased gradually to 100 beats/min at 30 sec following onset of deceleration. From this point, it gradually decreased in intensity. The subject was unconscious approximately 1 min during the decay. He was, however, completely asymptomatic following this centrifuge run, and standard ECG's and a double Master's test were normal during the routine follow-up exam. It should be mentioned that blackout to the point of losing peripheral vision is the point normally achieved during the bioassay runs, but unconsciousness for brief periods is sometimes seen. A subsequent bioassay run on BR-2 gave a completely normal ECG.

There was no impairment in posture equilibrium as measured with the rail walking and standing tests. The conditions of the experiment on the number of steps taken on the 0.75-in. rail before falling off, the number of seconds the subjects could stand with his eyes open on the 0.75-in. rail, and with his eyes closed on the 2.25-in. rail are shown in Table 7-VII.

Table 7-VII
POSTURE TESTS

GROUP	SUBJECT	DATE OF DETERMINATION								
		B-2			T-17			BR-3		
		Walk	Stand-Eyes Open	Stand-Eyes Closed	Walk	Stand-Eyes Open	Stand-Eyes Closed	Walk	Stand-Eyes Open	Stand-Eyes Closed
Control	JA	4*	48**	16**	–	–	–	6	36	100
	CB	10	22	51	–	–	–	14	70	103
	HK	15	55	98	–	–	–	15	33	105
	RM	14	82	42	–	–	–	14	21	48
Maintenance	RE	15	71	50	–	–	–	–	–	–
	GK	15	6	39	15	17	77	–	–	–
	BS	12	42	180	15	83	180	–	–	–
Therapy	GM	15	28	39	–	–	–	15	35	51
	LS	15	180	180	–	–	–	15	118	180
	FS	15	62	65	–	–	–	10	41	53

*Steps
**Time in sec.

A Master's two-step ECG taken before and after the experiment showed no abnormalities and no loss in exercise tolerance.

7.2.2 Diagnostic Tests

There were no significant changes in serum electrolytes, calcium, phosphorus, or in serum electrophoretic pattern determinations resulting from the conditions of the experiment. Tables 7-VIII and 7-IX summarize the results of the blood chemistries analyzed during the experiment.

Serum levels of chlorides and phosphorus showed the same trend as in the previous bed-rest study. Declines in serum chlorides were observed in all 10 subjects at the end of the experimental period. Observed changes were within the range of normal variations, and no clinical symptoms of electrolyte or fluid imbalance were seen. None of the subjects had emesis, abnormal fluid or electrolyte intake, or malfunctions of the urinary system which could result in these changes. Elevations in serum phorphorus were found in all subjects. Subject BS had a value somewhat above the normal range of variation, but was asymptomatic. All other subjects were within normal limits. A trend in serum electrolytes is apparent, but all values are within the normal range of variation.

The decline in A/G ratio during the course of the experiment resulted largely from an increase in the gamma globulin fraction; the cause of the decline is unknown. Variations in total protein, globulin,and albumin fractions were not consistently related to the conditions of the experiment.

During the first few days of the experiment, several of the subjects developed upper respiratory infections, probably viral, which were reflected in differential white counts. Otherwise, the complete blood counts showed variations within normal limits.

Routine urinalysis showed no remarkable changes attributable to the conditions of the experiment. Microscopic examinations of the urine were negative. All samples were free of sugar, acetone, and protein. Urine pH and specific gravity showed variations within a normal range.

Table 7-VIII
BLOOD CHEMISTRIES

GROUP	SUBJECT	DATE OF DETERMINATION																	
		B-3						T-14						BR-1					
		Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P	Na^+	K^+	Cl^-	HCO_3^-	Ca^{++}	P
Control	JA	142	4.5	107	27	4.9	3.9	145	5.5	103	26	4.8	4.7	146	5.4	100	29	5.0	4.9
	CB	143	4.6	107	28	5.0	2.1	143	4.8	103	26	4.8	3.7	143	4.5	100	28	4.8	3.6
	HK	144	4.3	108	29	5.3	2.9	140	5.1	102	23	5.0	4.4	145	5.8	102	22	4.9	4.3
	RM	143	4.2	107	27	5.2	3.7	143	4.4	102	24	4.7	4.7	151	4.9	101	23	5.0	4.1
Maintenance	RE	140	4.4	106	27	4.8	3.8	145	4.6	98	24	4.8	4.7	–	–	–	–	–	–
	GK	144	4.3	108	29	5.0	3.3	143	5.4	103	24	4.9	4.4	–	–	–	–	–	–
	BS	141	4.3	108	28	4.9	3.0	143	5.5	105	23	4.9	5.3	–	–	–	–	–	–
Therapy	GM	140	4.7	109	27	4.7	3.4	147	5.0	109	24	4.7	4.8	143	4.8	101	27	4.9	4.4
	LS	145	4.3	108	28	5.0	3.3	141	4.8	103	25	4.7	4.3	143	4.7	104	26	4.6	4.6
	FS	143	4.5	103	28	5.1	3.7	144	5.0	102	25	4.8	5.7	147	5.3	99	29	4.9	5.7

Entries are meq/L except P = mg%

Table 7-IX

SERUM ELECTROPHORESIS

GROUP	SUBJECT	B-3				
				Globulins		
		Total Protein	Albumin	Alpha 1	Alpha 2	Beta
Control	JA	7.2	4.5	0.4	0.7	0.9
	CB	6.9	5.0	0.2	0.4	0.6
	HK	7.8	5.5	0.2	0.3	0.8
	RM	7.2	5.2	0.2	0.4	0.6
Maintenance	RE	6.8	5.1	0.3	0.4	0.6
	GK	8.4	5.6	0.2	0.7	0.8
	BS	7.8	5.4	0.2	0.5	0.8
Therapy	GM	7.4	5.3	0.2	0.3	0.7
	LS	7.7	5.4	0.4	0.3	0.7
	FS	8.2	5.5	0.3	0.5	0.9

Entries are in gm except for A/G Ratio.

DATE OF DETERMINATION									
			T-14						
ns					Globulins				
Beta	Gamma	A/G Ratio	Total Protein	Albumin	Alpha 1	Alpha 2	Beta	Gamma	A/ Ra
.9	0.7	1.7	6.9	4.8	0.3	0.5	0.6	0.7	2.
.6	0.7	2.6	7.2	4.4	0.3	0.7	0.7	1.1	1.
.8	1.0	2.3	6.9	4.2	0.2	0.4	0.7	1.4	1.
.6	0.8	2.6	7.0	5.0	0.2	0.4	0.6	0.8	2.
.6	0.4	3.1	6.9	4.6	0.3	0.6	0.9	0.5	2.
.8	1.1	2.0	8.2	5.1	0.2	0.7	0.9	1.3	1.
.8	0.9	2.1	8.1	5.3	0.3	0.6	0.9	1.0	1.
.7	0.9	2.5	7.1	4.3	0.3	0.5	0.8	1.2	1.
.7	0.9	2.3	7.9	5.4	0.2	0.4	1.0	0.9	2.
.9	1.0	2.0	7.4	4.8	0.3	0.6	0.7	1.0	1.

2

		BR-1						
				Globulins				
Gamma	A/G Ratio	Total Protein	Albumin	Alpha 1	Alpha 2	Beta	Gamma	A/G Ratio
0.7	2.3	7.9	4.8	0.3	0.9	0.9	1.0	1.5
1.1	1.7	7.9	5.0	0.3	0.6	0.8	1.2	1.7
1.4	1.6	8.3	4.9	0.2	0.6	1.0	1.6	1.4
0.8	2.6	7.9	5.3	0.3	0.5	0.8	1.0	2.0
0.5	2.0	–	–	–	–	–	–	–
1.3	1.6	–	–	–	–	–	–	–
1.0	1.9	–	–	–	–	–	–	–
1.2	1.6	7.7	5.1	0.3	0.5	0.8	1.0	1.9
0.9	2.1	7.7	5.2	0.3	0.5	0.7	1.0	2.0
1.0	1.9	8.2	4.7	0.4	0.4	1.9	1.3	1.3

3

Analysis of the urine for calcium and phosphorus (inorganic) showed quantitative variations appropriate to a bed-rest experiment. These are shown in Table 7-X. Except for two subjects, the levels of the 17-ketosteroids and the 17-ketogenic steroids were within a normal range of variation. At the start of the experiment, subject HK's level of the 17-ketogenic steroid was below normal; at the conclusion of the experiment subject FS showed a below normal value for this same steroid.

After 14 days of bed rest and exercise, calcium output of the control and therapy groups was 103% higher than their baseline values. The maintenance group showed a 60% increase in calcium over baseline values. Because the only difference between the therapy and other two groups is the g-time integral, it must be tentatively concluded that periodic centrifugation favorably alters calcium output. Average output of the control group was 23.3 meq/L/24 hours, which is above normal limits; output of the therapy group was 17.3 meq/L/24 hours; output of the maintenance group was 14 meq/L/24 hours. After 24 days of bed rest and exercise, calcium output of the control subjects was 99% higher than their baseline values and 3% lower than their T-14 values. Calcium output of the therapy group was within normal limits at this time. Average calcium output of the control group was 22.5 meq/L/24 hours; output of the therapy group was 18.3 meq/L/24 hours. For the therapy group, this average is 6% higher than the previous determination on T-14 and 110% higher than the baseline determination.

A pronounced difference in phosphorus output was seen at T-14. The output of the control and therapy groups was 31% higher than their baseline values. The maintenance group showed an 18% decrease in phosphorus output. Average outputs in the control and therapy groups were 1.4 gms/24 hours and 1.2 gms/24 hours, respectively. The average output of the maintenance group was 0.81 gms/24 hours. After 24 days of experimentation, there were no appreciable differences between the control and therapy groups in phosphorus output. For the therapy group, phosphorus output on BR-2 was 8% higher than their baseline output and 7% less than the determination on T-14. Phosphorus output for the control group was 7% higher than baseline, and 26% less than the previous determination on T-14. These

Table 7-X
URINE CHEMISTRIES

GROUP	SUBJECT	DATE OF DETERMINATION											
		B-3				T-14				BR-2			
		Ca^{++} *	P**	17 *** Ketogenic Steroids	17 *** Ketosteroids Total	Ca^{++}	P	17 Ketogenic Steroids	17 Ketosteroids Total	Ca^{++}	P	17 Ketogenic Steroids	17 Ketosteroids Total
Control	JA	13.1	1.2	14	21	16	1.1	8	14	25	0.87	8	18
	CB	14.4	1.0	7	18	27	1.6	9	23	28	1.2	5	15
	HK	2.8	0.60	3	8	15	1.2	11	21	13	0.98	6	24
	RM	14.9	0.96	11	11	35	1.5	10	14	24	0.96	7	13
Maintenance	RE	4.5	0.62	3	6	12	0.45	9	15	–	–	–	–
	GK	15.9	1.4	13	22	17	1.0	13	18	–	–	–	–
	BS	5.9	0.93	7	12	13	0.97	10	19	–	–	–	–
Therapy	GM	12.5	0.86	8	11	24	1.1	10	18	19	0.68	7	13
	LS	2.8	0.57	8	14	13	0.94	11	20	16	1.2	5	17
	FS	10.8	1.6	12	25	15	1.5	13	21	20	1.4	1	5

*Meq/24 hours
**g/24 hours
***Mg/24 hours

data and those from the calcium analysis suggest that the maintenance regimen was more effective than the therapeutic regimen in preventing large calcium and phosphorus outputs. However, valid conclusions on metabolism are predicated upon having the subjects in calcium and phosphorus balance prior to experimentation.

Declines in plasma volumes in eight of the ten subjects at T-14 and T-17 ranged from 140 to 680 ml or 9 to 18%. Decrease in total blood volume for this same period ranged from 60 to 1,380 ml or 1 to 20%. Two subjects (GM and FS), both in the therapy group, showed no significant change in plasma or blood volume; the slight elevations (1 to 2%) shown by these two subjects during 17 days of bed rest and physical exercise are within the 5% accuracy reported in using the I^{131} method. Extracellular fluid decreased in all subjects during this period. The decrease ranged from 1,200 to 5,400 ml or 7 to 28%. Hematocrit decreased in eight of the ten subjects, was slightly elevated in one, and showed no change in another. Table 7-XI gives plasma, blood and extracellular fluid volumes, and hematocrits at four consecutive points in the experiment.

Since the control and therapy groups received the same treatment up to the 14th and 17th day, respectively, it is reasonable to combine their responses and compare these with the maintenance group. The average plasma loss for the control and therapy groups was 8%; the average loss for the maintenance group was 7%. Average loss of extracellular fluid for the control and therapy groups at this point in the experiment was 18%, as compared with a 15% loss in the maintenance group.

After 23 days of experimentation the control group showed a net average loss of 13% in plasma volume; no net loss was shown by the therapy group. Neither group showed a loss between BR-1 and the preceding determination. The control group showed an average net loss in extracellular fluid of 23% and no loss between BR-1 and the preceding determinations on B-3. The apparent lack of correlation between fluid compartments changes and cardiovascular function as measured by the tilt table is of interest (Reference 5-5). For example, subject GM showed a slight increase in blood volume as a

Table 7-XI

FLUID COMPARTMENTS

GROUP	SUBJECT	B-3				
		Plasma Volume†	Hematocrit*	Blood Volume	Extra-cellular Fluid	
Control	JA	3.89	45	6.85	20.7	..
	CB	3.85	47	7.01	19.1	.
	HK	3.47	46	6.21	19.0	..
	RM	4.34	44	7.51	18.6	..
Maintenance	RE	2.64	47	4.81	16.5	..
	GK	3.39	49	6.40	18.6	..
	BS	3.09	45	5.44	16.2	..
Therapy	GM	3.85	44	6.67	20.5	.
	LS	3.16	45	5.56	16.6	..
	FS	3.39	43	5.77	18.4	..

† Volumes in L
*Hematocrit in percent

DATE OF DETERMINATION							
T-14 & T-17				BR-1			
..sma ..ume	Hematocrit	Blood Volume	Extra-cellular Fluid	Plasma Volume	Hematocrit	Blood Volume	Ex cell F
..1	43	5.47	15.3	2.98	46	5.34	1
..0	46	6.27	13.8	3.70	45	6.51	1
..2	42	5.06	14.7	2.94	45	5.18	1
..6	43	6.58	15.5	3.98	45	7.01	1
..0	44	4.33	14.4	–	–	–	
..3	46	5.61	15.3	–	–	–	
..7	43	4.89	13.9	–	–	–	
. 0	44	6.75	17.4	3.72	46	6.66	1
..2	47	5.50	15.1	3.20	46	5.73	1
..8	43	5.93	17.2	3.48	43	5.93	1

TE OF DETERMINATION

T-14 & T-17			BR-1			
atocrit	Blood Volume	Extra-cellular Fluid	Plasma Volume	Hematocrit	Blood Volume	Extra-cellular Fluid
43	5.47	15.3	2.98	46	5.34	14.9
46	6.27	13.8	3.70	45	6.51	15.6
42	5.06	14.7	2.94	45	5.18	14.2
43	6.58	15.5	3.98	45	7.01	14.8
44	4.33	14.4	–	–	–	–
46	5.61	15.3	–	–	–	–
43	4.89	13.9	–	–	–	–
44	6.75	17.4	3.72	46	6.66	14.5
47	5.50	15.1	3.20	46	5.73	14.1
43	5.93	17.2	3.48	43	5.93	16.8

2

3

result of 14 days of bed rest and exercise but fainted after 15 min at 64° head-up tilt. Subject JA, who sustained an 18% loss in plasma, did not develop syncope during the tilt-table tests.

Changes in body weight are shown in Table 7-XII. Losses in body weight were progressive in all groups and ranged from 0.5 to 4.7 kg. Subject BS showed an 0.4 kg gain in weight. Subject JA, showing the largest weight loss, also showed the largest loss in plasma and extracellular fluid volumes. The control and therapy groups lost almost four times more weight than the subjects in the maintenance group; after 23 days of experimentation, the average weight loss was 3.8 kg in the control group and 3.6 kg in the therapy group.

7.2.3 Monitoring Tests

Blood pressure measurements made three times daily revealed no marked change. Resting heart rates varied between 50 and 70 beats/min with several individual variations. Heart rates while pedaling the bicycle ergometer were in the neighborhood of 160 beats/min, again with individual variations ranging from 135 to 200 beats/min on occasion. Respiration rates remained relatively constant at 14 to 18 breaths/min except during exercise. Oral temperatures ranged from 97° to 98.6°F.

Subjects who had participated in both experimental studies were asked to compare the reconditioning and maintenance regimen. Excerpts from their reports are as follows:

1. Subject BS

   "In comparing the two experiments, the second seemed harder mainly due to the scheduling of the runs and the exercise. It was difficult to get more than 3 or 4 hours of uninterrupted sleep at any one time during a 24-hour period. Until the rescheduling of the exercise there was the inconvenience of bathing four times a day."

2. Subject LB

   "One had to burn a fixed amount of calories each day; this meant utilizing muscles mainly in the legs; for me it meant adding muscular tone, not merely maintaining it. During the second study one could get no more than 3 hours of undisturbed sleep, as the periods between runs had to accommodate exercising on the ergometer, eating meals, allowing the nurses to take regular

Table 7-XII

BODY WEIGHT

GROUP	SUBJECT	DATE OF DETERMINATION				
		B-1	T-8	T-13	T-20	BR-2
Control	JA	78.27	76 10	75.05	75.23	73.76
	CB	78.98	78.20	77.75	77.94	77.13
	HK	72.45	69.60	69.50	68.85	68.34
	RM	84.05	82.30	80.00	80.50	79.34
Maintenance	RE	67.73	67.70	67.25	-	-
	GK	88.98	87.20	86.80	-	-
	BS	71.09	71.10	71.50	-	-
Therapy	GM	74.52	72.30	71.56	70.65	70.46
	LS	73.68	73.00	72.75	71.95	71.45
	FS	92.53	90.50	89.10	88.38	88.14

Entries are in kg.

medical data, baths, linen changes, etc. This lack of sleep combined with exhaustive ergometer exercise left one very tired and sleepy, so most of the time was spent sleeping. As a result there were many occasions when I rode the centrifuge barely managing to keep my eyes open. When I got out of bed after 12 days of lying in bed I felt surprisingly strong on my legs. My gait was erect and I could walk in a straight line without fear of losing my balance. There was not even a modicum of dizziness."

3. Subject GK

"In my opinion, this bed rest study was a very tiring and trying experience, much more so than the last 6-week experiment. The sleeping and exercise schedule was not at all conducive to ample sleep and rest. I am sure that I never got more than 4 consecutive hours of sleep during the entire 2 weeks. This, to me, was very trying, both physically and mentally."

4. Subject DE

"I adjusted very quickly to the 6-hour ride and exercise schedule."

The major use of the many thoughtful and cogent notes made by the subjects will be in selecting future subjects and in managing and staffing the biodynamic ward.

Medical summaries prepared by the duty nurse and augmented by the experimenters showed that the combination of exercise and the 6-hour ride schedule made this an arduous experiment for the subjects. It was difficult, for example, to get the subjects awake and alert for scheduled rides on the centrifuge. This was especially true for the 0630 and 0030 rides. The upper respiratory infections noted previously probably had little or no effect on the outcome of the experiment.

In recovery, subjects reported some stiffness and soreness of the joints, particularly the arch and ankles, during the first few days out of bed.

7.3 SUMMARY

A second pilot study was conducted to examine the influence of periodic centrifugation and exercise on physiological disturbances associated with recumbency. The subjects were 12 healthy, young men who were divided into one control group and two experimental groups. Subjects from all

groups were transported to and from the centrifuge; however, the maintenance group started periodic rides on the centrifuge on the first day of bed rest and rode for 13 days; the therapy group started riding the centrifuge after 17 days of bed rest and rode periodically for 6 days. The experimental groups rode the centrifuge 4 times/day, with 6 hours between successive rides; duration of each ride was 11.2 min. The level of acceleration was +4 g_z at the subject's feet. The integrated g-time was 3 g-hours. All subjects exercised on the bicycle ergometer while at bed rest and in the horizontal position. The energy cost of this exercise was approximately 700 kcal/day for each subject, and was scheduled at their discretion. All subjects exercised twice daily for 1 week prior to the study.

One subject was removed from the experiment on the 11th day of bed rest after experiencing a disturbance in cardiac rhythm and syncope during a maintenance ride of the centrifuge. Another subject voluntarily resigned on the 4th day of bed rest after experiencing vertigo. The remaining 10 subjects completed the experiment.

Master's two-step ECG's were obtained on all subjects and revealed no abnormalities and no loss in exercise tolerance as a result of the experiment. No impairment in postural equilibrium was evident during performance of the rail walking and standing test.

Functional tests conducted periodically during the experimental period revealed the following:

1. Use of periodic centrifugation and exercise during bed rest tended to prevent deterioration, in the maintenance group, of the mechanisms essential for circulatory control on the tilt table.
   A. Effects of centrifugation were indicated by a lack of syncope in the maintenance group of three subjects. In the groups not riding the centrifuge, three of seven subjects developed syncope and one showed signs of impending syncope at the scheduled termination of the tilt test.
   B. Effects of exercise were indicated by heart rate responses during tilt. Rates were always below 100 beats/min. This figure is in sharp contrast with the no exercise bed-rest study where rates in excess of 120 beats/min were common.

2. Comparison of the control and therapy groups after 23 days of experimentation showed that the protocol used in this study was not so effective as the earlier protocol in re-establishing orthostatic tolerance. The effects of exercise were indicated by the frequency of fainting in the control group. Two of the four subjects developed syncope. In the preceding study, 21 days of bed rest and no exercise produced syncope in four of the five subjects.

3. A trend in the direction of reduced tolerance to positive acceleration ($+g_z$) was noted after 14 and 23 days of experimentation. ECG abnormalities were seen in three subjects during bioassay runs after 14 days, but none were seen during bioassay runs following 23 days of experimentation.

4. Subjects in the experimental groups reported no abnormal complaints during maintenance and therapeutic centrifugation, and observational data support this position, for example, subjects read books during the 11.2 min rides; they reported that the 6-hour ride schedule and the exercise regimen made this an arduous experiment.

5. Loss of calcium in the urine was, on the average, half as great in the maintenance group after 14 days of experimentation; and half as great in the therapy group after the start of centrifugation. The control group showed a calcium loss of 99% above their control values during 23 days of bed rest and exercise; the same trend is apparent in urinary phosphorus.

6. Both exercise and its combination with centrifugation provided partial protection against expected losses in plasma and blood volumes. Average plasma losses were 7% in the groups not riding the centrifuge and 6% in the maintenance group; this is in contrast with the no exercise bed-rest study where the losses in plasma volume were 12%.

7. Losses in body weight during the experiment were progressive and ranged from 0.5 to 4.7 kg. Average weight losses in the control and therapy groups were almost four times the average losses in the maintenance group; after 23 days of experimentation the differences in weight loss between the control and therapy groups were insignificant.

8. There were no significant changes resulting from the conditions of the experiment in serum electrolytes, calcium, phosphorus, or in serum electrophoretic patterns; microscopic or qualitative analysis of the urine for sugar, acetone, or protein, urinary specific gravity, or pH; resting blood pressures, heart and respiration rates, or oral temperatures; or cardiovascular changes produced by the Flack test.

9. Recovery or return toward control levels of physiological function took place within the 10-day recovery period.

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SECTION VIII

SPACE-BASED CENTRIFUGE

8.1 GENERAL

How dependent is man on the force of gravity? Gravity is such an ubiquitous force in normal physiological functions that little is known about the biological effects of its removal. This is one question that can only be answered satisfactorily in an orbital laboratory. Moreover, an answer is requisite for planning more ambitious flights -- a stay of many months in space, for example, or a trip to Mars. Cogent research requires the production of a physiologically valid acceleration and as yet, the centrifuge is the only practical method of producing such an acceleration in the space environment. The feasibility of including a short-radius centrifuge in manned orbital laboratories is being studied from the research, training, and biomedical points of view.

Studies primarily concerned with a quantitative demonstration of the feasibility and general effectiveness of the centrifuge are summarized as follows:

1. Stress-duration curves constructed by the Aeromedical Laboratory at Wright Field show that subjects can tolerate levels of $+1g_z$ and $+2g_z$ and the 256% heart-to-foot acceleration gradient for the arbitrary 2 hours set by the protocol. Above $+3g_z$ (referenced to the feet), a logarithmic line of decreasing tolerance can be constructed for the mean durations (Reference 2-4).
2. Measurement of tolerance to positive acceleration is possible on a short-radius centrifuge using a low-intensity bioassay light and a single gradual onset run to blackout (Reference 8-1).
3. A study of the effects of acceleration gradient and coriolis force on performance show that these two physical factors have a detrimental effect of the order of 0.07 sec on the time to reach a control However, this low-level differential time is not of sufficient magnitude

to affect the use of a short-radius centrifuge as a re-entry training device aboard a laboratory (Reference 8-2).

4. Based on approximately 3,000 runs on the centrifuge, a steep heart-to-foot acceleration gradient does not preclude movement of the head, arms, and legs; and, motion sickness is not a problem for the well-trained individual when exposed to high angular rates and modest head or limb movements (Reference 2-7).

5. A two-radius method for measuring body mass is being examined experimentally. Accuracy of the method is placed at ±1% for a 180-lb man. With the two-radius method, the distance from the center of rotation to the center of mass of the man, a value difficult if not impossible to obtain, is not required (Reference 2-7).

6. The reconditioning potential of the centrifuge has been explored. For as little as four 7.5-min rides each day on the centrifuge, the deterioration produced by bed rest in the ability of the subjects to tolerate 90° head-up tilt for 20 min was largely alleviated as judged by syncopal episodes. However, heart rates, pulse pressures, and plasma volumes were not restored to control levels. Subjects receiving +4 g_z showed less lability in blood pressure and heart rate during the tilt-table tests than did the subjects exposed to +1 g_z (referenced to the feet).

7. The maintenance potential of periodic centrifugation and exercise has been assessed. The effects of centrifugation were indicated by the lack of syncope for those subjects who had ridden four times a day. In the group not riding the centrifuge but exercising, three of seven subjects developed syncope, and one showed signs of impending syncope at scheduled termination of the tilt test. Effects of exercise were indicated by heart-rate responses during tilt. Rates were always below 100 beats/min. This figure is in sharp contrast with that found in subjects who rode the centrifuge but did not exercise. Here, rates in excess of 100 beats/min were common. Exercise, with centrifugation provided partial protection against expected losses in plasma and blood volumes.

8. A parametric study of the power requirements of a short-radius centrifuge reveal that the centrifuge would have an empty weight of 155 lb; a peak power consumption at 0.2 g/sec rate of onset of acceleration of 436 watts; and 5.85 Whr consumption during a 7.5-min run at 4 g.

8.2 FUTURE RESEARCH

Although significant work is in progress to evaluate and develop methods for either diminishing or preventing physiological adaptation in space, much more needs to be done to confirm and refine them. A direction future research might profitably take is toward a thorough evaluation of centrifugation and exercise, and their combination in both therapeutic and maintenance regimens to include the following

1. The physiological effects of exercising while riding the centrifuge.
2. Influences of frequency, duration, and magnitude of periodic exercise and centrifugation on orthostatic tolerance.
3. The conceptual design of centrifuge research programs as part of the overall biomedical and physiological evaluation to be conducted in orbit.
4. Auxiliary uses of the centrifuge and their contributions to mission success, for example, sleep studies during centrifugation at low angular rates.
5. Development and demonstration of the techniques necessary for use of centrifugation in evaluating cardiovascular status in orbital operations.

Further research, both ground-based and that based on space flight, is clearly needed to define the roles of the short-radius centrifuge in flights of 30 days or greater. The potential includes its use as an adjunct to other countermeasures, as a reasonably accurate mass measuring device, and for evaluation of cardiovascular status. Early realization of this potential could enhance both the mission success and the cost and effectiveness of extending manned operations significantly beyond 30 days, that is, to 90 days and longer.

8.3 REFERENCES

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APPENDIX

CLINICAL PROBLEMS ENCOUNTERED DURING THE STUDY

A stated purpose of these two studies is a determination of the deleterious effects on man, if any, of exposure to acceleration on the short-radius centrifuge. During the second of the two bed-rest studies, there have been five incidents that bear on this purpose. They are reported in this appendix so that the specialist in aerospace medicine can become acquainted with the details of each case and evaluate the professional position taken by the physicians at Douglas Aircraft Company's Advance Biotechnology Department.

A.1 CASE REPORTS

Individual case histories for the five subjects participating in the experiment are as follows:

1. Case No. 1, NK -- Subject NK withdrew voluntarily from the program at 1400 on January 15, 1965 (T-4). He stated that he did not feel like continuing because of "dizziness". He also stated that registration for the second semester at UCLA would prevent him from continuing with the program. After withdrawing from the program, he consulted an attorney who stated in a letter that the subject had incurred disability as a result of his participation in this research.

   Subject NK entered the program on January 9, 1965 (B-1) and was placed in the maintenance group. At that time, he stated he was feeling quite well and had no problems or complaints. He was tested on the tilt table on January 9, 1965 (B-1) and tolerated this procedure well. On January 10, 1965 (B-2), the subject participated in two rides on the centrifuge as did all subjects involved in this program. The first ride was a maximum of $+6g_z$ and the second ride up to $+8g_z$. He tolerated these rides quite well and showed no after effects other than transient dizziness lasting a few minutes. He participated in a rail-walking test several hours after these rides and did as well as other members of the maintenance group. On January 11, 1965 (B-3), subject NK participated

in tests to determine tolerance to positive acceleration using the short-radius (4.5 ft) centrifuge and the modified low-intensity central-light bioassay techniques. He was taken to $+4g_z$ (at heart level) and did not lose the central light. He had no complaints during the run other than some pressure on his calves and feet, and had no symptoms or complaints after the run.

On the evening of January 11, 1965 (B-3), radioisotopes were injected intravenously for determination of intra- and extra-cellular body fluids. Approximately 1 or 2 hours after these injections, he stated his vision was different and that objects in his visual fields appeared to be "wavering" or as visualized "under water." These symptoms lasted approximately one-half hour then disappeared and did not recur. At 0630 on January 12, 1965 (T-1), the subject began participating in the standard maintenance rides on the centrifuge which were scheduled for every 6 hours during 24 hours, for a duration of 11.2 min and at an intensity of $+4\ g_z$ referenced at the feet. The ride was repeated at 1230 on the same day, and the subject tolerated both rides quite well and did not complain of any symptons before, during, or after the rides other than the slight pressure on his calves and feet. At 1830 on January 12, 1965 (T-1), the subject again rode the centrifuge. At this time, however, the subject was accelerated to $+3.6\ g_z$ referenced to the subject's heart rather than the feet. Total time from starting the centrifuge to deceleration was 2 min. The run was stopped because the subject complained of discomfort in his feet and legs which were then wrapped with ace bandages. Another similar run ensued and was terminated 2 min after start of rotation. During both of these runs, the subject's only complaints were the lower-extremity discomfort. Another subject riding with NK during both of these runs noted some pressure of the lower extremities but no other symptoms. At 0030 on January 13, 1965 (T-2), another $+4\ g_z$ (at the feet) ride was taken by the subject and no symptoms were noted before, during, or after this run. At 0630 the following morning, the subject reported no symptoms other than mild lower-abdominal discomfort during this run which disappeared immediately after. He stated he felt dizzy and nauseated after this ride but ate breakfast. He vomited twice approximately one-half hour later. All further rides on the centrifuge were then cancelled until his symptoms of vertigo were gone. He improved later this same day and stated that the dizziness and nausea were improved. The following day, January 14, 1965 (T-3), the vertigo was much better, although he did vomit once.

On January 15, 1965 (T-4), he stated the "dizziness" was much improved and he did not feel nauseated. Later, he

suddenly decided to withdraw from the program, stating as his reasons, "dizziness" and academic obligations. He arose from bed and stated he was somewhat unsteady on his feet and felt dizzy. He was seen by a local physician specializing in internal medicine who examined him and felt this was a viral labyrinthitis and prescribed dramamine. Several days later, he again developed an episode of dizziness and was referred to a neurologist who saw him on January 19, 1965. He found no evidence of primary neurological deficit and felt that, in all likelihood, this subject had a hemorrhage into his vestibular apparatus, probably in one of the semicircular canals of the left ear giving him positional vertigo. He was then referred to a physician specializing in ENT, and after repeated efforts by the Douglas staff and his own lawyer's suggestion to see this consultant, he finally did so on February 15, 1965. His ENT examination was normal. A vestibular function test was not performed in view of his normal hearing. It was the ENT specialist's impression that no permanent damage had occurred that was measurable, and no medication was indicated.

After leaving the program, subject NK applied for temporary disability payments under the Workmens' Compensation laws which he received from January 23, 1965 through February 15, 1965. He received no payments from January 16, 1965 through January 22, 1965 because of the 1-week waiting period as prescribed by law. On March 12, 1965, he was again seen by the ENT consultant, and a vestibular function test was performed. His examination at this time showed no measurable physical defomity. He was advised by the ENT consultant to contact a physician during any attack of vertigo so that nystagmus could be observed to establish the validity of his attacks. On April 13, 1965, he was seen by a neurosurgeon who found fine nystagmus on far-lateral gaze to either side. He otherwise was in good health. On April 27, 1965, he was seen by another neurosurgeon and his neurological examination was normal. He was feeling well except for periods of forgetfullness or "amnesia" lasting 1 to 2 min which, he states, he has noticed since his last ride on the centrifuge. He also stated that his memory is not as good as prior to the experiment and that he had periods of disorientation until recently. This additional history, not mentioned by subject NK previously, was stated by the subject during visits to both neurosurgeons on April 13, 1965 and again on April 27, 1965. An EEG was obtained on April 28, 1965 and was reported as abnormal. The record was a very low-voltage EEG. When the gain was increased, there were 4- to 6-cps general slow waves in all leads. There was no focus of abnormality. A repeat EEG will be obtained in 8 to 10 weeks.

This subject had between 100 and 125 rides on the centrifuge between February 1964 and January 1965 with no after effects.

The above symptoms could have resulted from a viral labyrinthitis. This appears to be the most logical explanation. Although one consulting neurosurgeon felt subject NK's symptoms were caused by hemorrhage into the vestibular apparatus, it should be noted that this diagnosis was made on the basis of a history presented by the subject (".... was exposed to as much as 14 gravities of force".) and not corroborated by the accelerometer data taken during these particular runs. Moreover, during these runs, the force at the head is less that 1 g since the head is near the center of rotation. As a result of this position, there is, therefore, practically no increase in pressure within the vasculature of the inner ear capable of producing the alleged hemorrhage. Factors contributing to a diagnosis of viral labyrinthitis are the facts that, at the time of development of his symptoms, several other subjects had what appeared to be viral upper-respiratory infections as verified by white blood counts and negative throat cultures for pathogenic bacteria. Repeated neurological examinations have revealed no abnormalities except fine nystagmus during lateral gaze observed by one neurosurgeon. Vestibular function tests showed no measurable deformity. Although the EEG was reported as abnormal, the significance, if any, of this finding, plus his complaints of "amnesic spells," disorientation, and poor memory can not be postulated until a repeat EEG is obtained in 8 to 10 weeks.

2. Case No. 2, LB -- Subject LB entered the program on January 9, 1965 (B-1) and participated in all baseline testing with no difficulties. He was placed in the maintenance group and began his scheduled rides 0630 on January 12, 1965 (T-1) every 6 hours, day and night. He was riding with subject NK during the 1830 ride on January 12, 1965 (T-1) which is described above. He had no after effects from this and continued with the daily maintenance rides.

At 0700 on January 22, 1965 (T-11) during a routine maintenance ride,he developed an asystole which lasted 20 sec. Just prior to the asystole, he stated he was nauseated and felt as if he were about to black out, which is what occurred. The centrifuge was immediately braked to a stop. He was unconscious for approximately 2 to 3 min. After being returned to his bed, he vomited three times. He then stated that prior to this ride he felt somewhat nauseated but did not want to mention it to the investigators.

The following is a verbatim report, dated January 27, 1965 (T-16), of a board-certified cardiologist:

"This is a report on Mr. Lalbeharry Baboolal, weight 138, height 67-1/4 inches, a 23 year old man who has been on your centrifuge studies.

Physical examination showed a well developed and nourished man. Fundi showed no evidence of disease of the blood vessels, no edema. EOM normal, no nystagmus. Pupils react to light and accommodation. There is no weakness of the facial muscles or groups. Tongue protrudes in the midline. Examination of the neck shows no distention of the blood vessels, movements are normal. Heart: PMI in just inside the MCL, rate is 80, sounds are normal. Blood pressure was 124/78 and pulse 76. Lungs were clear. Reflexes were normal throughout (knee: KK normal with agumentation, but Gordon, Babinski and Oppenheim were normal).

The electrocardiographic tracing taken while in the centrifuge starts with a rate of 94, PR interval of .15 and QRS of .08 seconds. This gradually slows until the rate is approximately 40 when suddenly there is no QRS complex for 3.6 seconds. This is followed by P wave of different shape and PR interval. QRS-T is the same. There is then a period of 9.2 seconds where there are some irregular markings on the tracing that may represent a QRS complex, however, it is not until another 7.4 seconds has gone by that there is a true QRS complex. The tracing taken one hour following the episode just related was perfectly normal.

Conclusions: This man had a cardiac arrest during a run with no evidence of permanent damage."

3. Case No. 3, GK -- Subject GK entered the program on January 9, 1965 (B-1) and was placed in the maintenance group. He completed all preliminary baseline studies with no difficulties. On January 25, 1965 (T-14), he was tested for $+g_z$ tolerance by means of the modified-light bioassay method. Blackout occurred at +3.6 g_z, and deceleration began immediately. At this point, bradycardia developed followed by asystole for 20 sec. The subject became unconscious, but by the time the centrifuge braked to a stop, he was alert again. He had no abnormal symptoms or findings after the run. He ate breakfast immediately and felt quite well during the remainder of

the study. He was seen by a cardiologist who found no abnormalities. ENT consultation again revealed no abnormalities.

The following is a verbatim report, dated January 27, 1965 (T-16), of a board-certified cardiologist:

"This is a report on Mr. Guy King, weight 196, height 69-1/4 inches, a 22 year old man who has been on your centrifuge studies.

Physical examination shows a well developed and nourished young man with no hearing or visual effects. Normal light reflex. Fundi showed normal blood vessels. EOM normal. Tongue protrudes in the midline, there is no facial weakness. Neck -no pulsating vessels seen or felt. Chest is clear. Examination of the heart shows the PMI at the MCL, sounds are clear. Blood pressure is 142/84. Tendon and superficial reflexes are normal throughout. Vibratory sense normal throughout. Oppenheim and Babinski normal throughout.

Review of his electrocardiographic tracings: At the first run showed a rate of about 60, a PR interval of .20, QRS of .07 and a QT of .34 and at the end of the first run the pulse rate was 70 and there was little change in any of the components. During the latter part of Run No. 2 the pulse gradually increased until it was going at the rate of 126 with a PR interval of .16, QRS of .07 and a QT of .28. Suddenly the shape of the P wave changes (is inverted), QRS complex remains the same. Following this abnormal complex, the heart for almost 4.5 seconds went into cardiac standstill and following which a QRS complex similar to the usual complex occurred without a P wave, then due to AC hum and extraneous note on the film it is impossible to state the exact happening. After another pulse, the heart began to beat normally with a PR interval of .16, QRS .07 and a QT of .32 which gradually slowed, and at the end of the tracing he had a rate of about 60 with a PR interval of .19, QRS of .07 and a QT of .34.

Conclusions: I find evidence of cardiac arrest on the elctrocardiogram. Physically his vestibular mechanism is normal. Cardiovascular system is normal with the exception of slightly elevated blood pressure, pulse is 66. Electrocardiogram showed no evidence of permanent damage. Neurological examination was normal."

5. Case No. 4, BS -- Subject BS entered the program on January 9, 1965 (B-1) and participated in all baseline studies without difficulty. He was placed in the maintenance group and began his centrifuge rides at 0630 hours on January 12, 1965 (T-1). No difficulties were experienced until a bioassay run at approximately 0830 hours on January 25, 1965 (T-14).

The following is a verbatim report dated January 27, 1965 (T-16) of a board-certified cardiologist:

"This is a report on Mr. Bill Schubert, weight 156, height 69-1/2 inches, a 22 year old man who has been on your centrifuge studies.

Mr. Schubert comes in for examination because during one run his electrocardiogram became peculiar.

Physical examination revealed a well developed and nourished young man. Fundi showed no evidence of blood vessel disease or edema. Pupils react to light and accommodation. There is no nystagmus. There is no weakness or abnormal movements of the muscles of the face. Examination of the neck revealed no pulsating blood vessels. Chest was clear. On examination of the heart, the PMI was at the MCS and there was a split 1st sound heard best at the mitral area. Blood pressure was 122/78. Reflexes were normal throughout the body. Grip in both hands equal and normal. Gordon, Babinski, and Oppenheim were normal.

Electrocardiographic tracing taken during the run shows a beginning rate of about 62 with a PR interval of .16 QRS of .08 and QT of .30 seconds. After a few complexes one T wave is inverted. Whether this is an artifact I do not know. The rate gradually speeds up and finally reaches 166. There are notches in the T waves which I believe are buried P waves within the T wave and the PR interval is .13 seconds. Following the part of the tracing marked with DK, the heart begins to slow but peculiarly the relationship between the P wave and the QRS complex becomes more close and occasionally complexes are present without evidence of P wave.

I believe this represents complete disassociation with an auricular rate a little slower than the ventricular rate. At one point the auricular rate is about 62 and the ventricular rate is about 63 or 64. Gradually the evidence of P waves disappears and when it does occur there is inverted P waves in the tracing as well as upright P waves. I believe this represents a complete disassociation

with nodal rhythm and sinus rhythm which are not related. Later in the tracing there are apparent P waves from posterior auricle lows. This probably means there are two foci within the auricle which are initiating impulsations, one in the SA node and one in the posterior or left auricle. Gradually the PR interval lengthens and there is a P wave before each QRS complex. At first the PR interval is .13 and gradually increases to .14 and remains there until the end of the tracings

Conclusions: I believe that this is due to some autonomic nervous system stimulation and is not due to disease in the heart. I would recommend that the experiments continue and I see no danger to the individual. An electrocardiogram taken this morning is perfectly normal."

5. Case No. 5, HK -- Subject HK entered the program on January 9, 1965 (B-1) and participated in all baseline studies without difficulty. He was placed in the control group and began bed rest on January 12, 1965 (T-1). No difficulties were experienced until the bioassay run of January 27, 1965 (T-16).

HK had a completely normal ECG prior to centrifugation on January 27, 1965 (T-16). At a peak of +3.2 g_z during the bioassay run, the ECG was normal and showed only the usual changes of decreased R waves and increased heart rate from 83 to 140 beats/min. Upon decay from peak acceleration, the heart rate rapidly slowed from 140 to 100 beats/min. in 6 sec., at which point bradycardia developed to a minimum of 28/min for 2 beats. The heart rate then increased gradually to 100 beats/min at 30 sec following the decay of acceleration. From this point, it gradually slowed to 78 beats/min with a moderate sinus arrhythmia being noted which slowly decreased in intensity.

The subject was unconscious approximately 1 min during the decay. However, he was completely asymptomatic following the centrifuge run, and it should be mentioned that blackout to the point of losing peripheral vision is the point normally achieved during the bioassay runs, but unconsciousness for brief periods is also common. Standard ECG's and a double Master's test were normal during routine follow-up examination.

This subject had a third bioassay run on February 5, 1965 (BR-2), at the end of the study, which he tolerated well and during which his ECG was completely normal.

A.2 NOTES

All ECG's were telemetered by a small FM transmitter mounted on the centrifuge and were chart recorded. Electrodes were attached to the skin in the MX position except when skin reaction required them to be mounted in the fifth intercostal space and midaxillary line.

The following findings were taken as evidence of abnormality:

1. Ischemic S-T segment depressions over 1 mm or the increase over 1 mm of a previously present S-T depression.
2. The appearance of S-T segment elevation over 1 mm or the elevation of a previously depressed S-T segment.
3. T-wave inversion.
4. The inversion of a previously negative wave to an upright configuration.
5. The appearance of numerous ectopic beats.
6. Marked changes in the configuration of the QRS complex.
7. Asystole or bradycardia below 40 beats/min.

The following were considered as suggestive of abnormality:

1. S-T depression observed during occasional beats.
2. T-wave inversion during occasional beats.
3. Marked alteration in T-wave contour.

Three of the subjects who developed ECG abnormalities while riding the centrifuge were evaluated by an otologic clinic. Tests obtained were audiometry, Bekesy Tests, Short Increment Sensitivity Index, speech tests, electronystagmography, and caloric testing.

Verbatim clinical impressions of the examining otologist are as follows:

1. Subject GK -- "Audiometric evaluation revealed better than average pure tone responses bilaterally. There was a Type I Bekesy bilaterally. In the right ear, the SISI scores were 5% at 4000 cps and 40% at 2000 cps. In the left ear, the SISI scores were 30% at 4000 cps and 75% at 2000 cps. The electronystagmograph produced normal responses bilaterally. There was no spontaneous nystagmus.

   Impression: Normal hearing and vestibular responses with the exception that the SISI score was somewhat elevated, indicating the possibility of recruitment. This is negated, however, by the Bekesy and speech tests which were 100% in both ears."

2. Subject BS -- "Pure tone audiogram was normal except for a slight high frequency loss above the 2000 cps level. Speech tests were normal. Type I Bekesy in both ears. The SISI score was 0% at 4000 in the right ear and 50% at 4000 cps in the left ear. Electronystagmography revealed a very slight spontaneous nystagmus in the supine position and with the head hanging to the right.

   Impression: The amplitude of the caloric nystagmus is reduced bilaterally, but more on the left side, indicating a 52% left canal paresis. However, due to the small amplitude of the nystagmus, it is questionable as to whether this in fact represents a real paresis."

3. Subject LB -- "Pure tone and speech tests were normal bilaterally. The Bekesy in the right ear is questionable, being between that of a Type I and Type II. The Bekesy in the left ear is normal. Electronystagmography revealed no spontaneous nystagmus. Caloric responses failed to produce any nystagmus with exception of a very slight response in the right ear to warm water at 44° Centigrade.

   Impression: Normal hearing with greatly decreased response to caloric stimulation in both ears."

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N. A.	Assistant for Bioastronautics and Aerospace Medicine, Space Systems Division; A.F. Systems Command, L.A.A.F. Station, California

13. ABSTRACT Five studies concerning the potential of a centrifuge in an orbital laboratory were conducted. The first three studies include consequences of heart-to-foot gradients on tolerance to positive acceleration, a parametric study of the power requirements of a short radius centrifuge, and a technique utilizing the centrifuge for determining body mass in a null gravity state. The salient generalizations from studies in which bed rest was used as the analog of null gravity were presented. The fourth study was conducted to study the influence of periodic centrifugation as a method of alleviating physiological disturbances, with emphasis on the cardiovascular system, brought about by 20 days of bed rest. It was shown that motion sickness in the subjects was not a problem when exposed to high angular rates of rotation. Deterioration produced by recumbency was alleviated by periodic centrifugation, and subjects exposed to $+4g_z$ four times daily showed less lability of blood pressure than did those receiving less acceleration. The fifth study extended the results of the fourth study by increasing the integrated g-time, added approximately 700 kcal of exercise, and distributed the rides over a 24-hr period as contrasted with the 8-hr schedule of the prior study. A maintenance group started riding the centrifuge on the first day of bed rest. A therapy group started riding after 17 days of bed rest. A control group was not centrifuged. Periodic centrifugation tended to prevent cardiovascular deconditioning in the maintenance group as indicated by tilt-table responses in this group as compared to the noncentrifuged group. The final section examines the evidence for a space-based centrifuge and its potential to enhance both mission success and the cost and effectiveness of extending manned operations significantly beyond 30 days.

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